AgroEcoTech:
How can Technology Accelerate a Transition to Agroecology?

Report for The Soil Association

July 2021

Acknowledgements from the Authors

We would like to sincerely thank the advisory group who have been essential to the development of this report. It is their considerable knowledge, experience, and ongoing dedication to enhancing agricultural sustainability that has made this report what it is.

Alastair Cooper, Andrew Burgess, Ben Raskin, Carly Scott, James Elliot, Jonathan Gill, Jonathan Hughes, Jyoti Fernandez, Katrin Burt, Luke Halsey, Matthew Smith, Rich Osborn, Sonny Masero, Tom MacMillan, and William Kendall, your ongoing support for this project has been invaluable.

Cumulus would also like to thank The Soil Association for facilitating and trusting us with this work. Joanna Lewis and Gareth Morgan, your support, enthusiasm, and guidance throughout this project are deeply appreciated.

We would also like to thank all those who participated in the co-design workshop; your insights and ideas have been inspiring and valuable.

George Chanarin and Paul Silcock,
Cumulus Consultants.

CUMULUS CONSULTANTS
LAND - ENVIRONMENT - ECONOMY

Cumulus Consultants Ltd

1 Gainsborough House, Campden Business Park
Battle Brook Drive
Chipping Campden
Gloucestershire GL55 6JX

Telephone: **+44 (0)1386 277970**
Email: **info@cumulus-consultants.co.uk**
Web: **www.cumulus-consultants.co.uk**

Cover image: Male mechanical engineer with sustainable agricultural robot in field © This is Engineering/Flickr

Contents

Foreword

Approaches to farming that learn from 'natural' ecological systems – agroecology or regenerative farming, pioneered by so many organic farmers – have often been assumed to be 'anti-science' or 'anti-technology'. Now science is finally catching up with the complexity of nature.

Technologies like next-generation DNA sequencing and Artificial Intelligence are helping us begin to appreciate the mind-boggling complexity of the soil microbiome and its role in plant nutrition. This in turn links to our own gut microbiome and its newly revealed role in human health. Technology is proving and making visible to us the importance of ecology and the complex sophistication of natural systems.

The time is right, therefore, for agri-food tech to work in service of this complexity and support a transition to more ecological farming and a healthier food system. For too long, as the report's authors argue, "diverse, agroecological systems have not been well served by the application of labour reducing technologies." We have ripped out hedgerows and compacted our soil with heavy machinery to make farming work for tech. Now we need to make tech work for a farming and food system that in turn works for the climate, nature and health.

I find it tremendously exciting that a whole new generation of technologies, especially in robotics and remote sensing and AI, could help farmers manage complexity and support them to farm in a more ecological, regenerative way. Our new Soil Association Exchange (SAX) venture aims to empower farmers and foresters by offering a digital suite of tools to help them collect scientifically rigorous data to show their impact on the land and keep adapting to improve this. Digital food hubs and dynamic food procurement could build markets for the produce of more ecological farming and leverage the £2bn-plus public sector food spend more for the public good.

One key recommendation from this report is that the Agriculture Bill's principle of 'public money for public goods' is now properly applied to public sector agricultural R&D which is over £320 million. This could create an opportunity to bring to market technologies that may be low market value but with big potential public benefits.

However, in our enthusiasm for the possibilities of new tech, we mustn't overlook the crucial role that farmers' hands-on experience and visual judgement will continue to play. And of course, the innovation we need for agroecology goes far beyond tech solutions. Often, we are too quick to assume there is a tech barrier, when more rigorous 'problem definition' – with farmers in the driving seat - would first search for solutions in farm management systems and practices. The Soil Association is proud to lead the Innovative Farmers partnership, putting farmers in the driving seat of their 'field labs' with researchers assisting with trial design and statistical analysis.

The authors of this report are technology optimists and emphasise that genome editing, which along with GM has always been understandably controversial in organic circles, may have a role to play. All the more important, then, is their message that it must not be allowed to distract from system transition, getting to the 'root cause', which would prevent the problem in the first place.

This research is a first step in an ongoing enquiry. Now we invite you to join the debate and help us answer the big questions that remain. Above all, tech design needs to start with the right definition of the 'problem'. Please do share your thoughts on the real problems blocking agroecology and sustainable diets where tech could be the solution: **#AgroEcoTech**

Helen Browning
Group CEO, Soil Association

Introduction from the Soil Association

"There were profoundly important questions about the potential effects of each new technology which it was nobody's job to ask or answer. There was no mechanism for farmers or ecologists to judge whether a technology or new farming practice was on balance a 'good' thing or a 'bad' thing, and we didn't really know when we had crossed the invisible threshold from one to the other."

James Rebanks, English Pastoral

The National Food Strategy in England has set out an ambition for transformational change in our food and farming system to achieve net zero, restore biodiversity and improve our nation's dietary health in the wake of Covid. The Strategy emphasises that agroecology has a central contribution to make to that ambition and that "agroecological methods ... have been starved of investment up to now". Agroecology needs to be at the centre of the innovation agenda for agriculture and food, not in the margins as it has been to date.

The assumption is often made that agroecology and regenerative agriculture are fundamentally low-tech scenarios, in contrast to sustainable intensification scenarios predicated on precision farming technologies. In commissioning this research, we set out to test and challenge that assumption. We wanted to ask: which technologies are most likely to provide opportunities for agroecological transition and which could become barriers? How does governance need to be structured to facilitate these opportunities and remove the barriers?

What is Agroecology?

Imagine a landscape where farming is working in true harmony with its surroundings. Soils, trees and grasslands soak up carbon and provide welcoming habitats for wildlife. Grazing cows and sheep recycle nutrients, reducing the need for synthetic fertiliser, and maintain biodiverse pastures. Pigs and poultry live mostly on waste, competing less with humans for food. This agroecological mixed farming model brings multiple benefits. Better soil health improves the land's ability to hold water, helping to prevent flooding. It also improves food productivity and sequesters more carbon from the atmosphere. Reducing pesticides and herbicides by using natural processes to manage 'weeds' and 'pests' has significant benefits for biodiversity.

Agroecology means farming in ways that learn from and enhance natural systems. Organic farming and agroforestry are the best-established examples within an agroecological spectrum which spans from simpler modifications of existing practice, to a complete remodelling of our food and farming system; regenerative farming, permaculture, conservation agriculture are all examples. Organic farming, uniquely, is defined in law and backed by certification and inspection.

The 'Ten Years for Agroecology in Europe' modelling by French think tank IDDRI demonstrated that it is possible to transition all of Europe's farms to agroecology and still feed a growing population a healthy diet while radically reducing our food's climate and nature footprint – but only if strides are taken this decade to achieve a 'Ten-Year Transition' to agroecology and sustainable diets. This scenario has been mapped for the UK by IDDRI, working with the Food, Farming and Countryside Commission, in Farming for Change: mapping a route to 2030.

Key insights from the research

It is clearer than ever from the findings of this research that few technologies are inherently 'good' or 'evil'. It is how they are developed and used that matters. Technologies can and will accelerate the transition to agroecology that we so urgently need, but only if we get the governance right. The scenario analyses for the case study technologies in this report highlight how different approaches to governance could have very different outcomes, favouring intensive farming or diverse, agroecological farming; consolidating control in the hands of fewer powerful actors or supporting a more equitable food and farming system.

There are clearly huge opportunities for agroecology from a new generation of technologies like robotics and remote sensing that – if designed with farmers and governed well for equitable access – could overturn decades of standardisation and allow farmers to diversify and manage more complexity in their farm businesses. On the demand side, digital food hubs and dynamic food procurement could help farmers connect with citizens and flexibly supply fresh, seasonal produce into local schools and hospitals. The Soil Association is proud to chair the Dynamic Food Procurement National Advisory Board and hugely encouraged by Crown Commercial Services' support for a South West food hub pilot that could lead to a national roll-out.

On the risk side, with a technology governance gap, or a narrow 'problem definition' that fails to join the dots between climate, nature and health, emerging technologies could lock us in to business-as-usual crop monocultures and industrial livestock farming. Bioenergy and gene editing remain at risk of being used as 'silver bullets' that mask the symptoms of a farming system that doesn't work for climate, nature, health and animal welfare. For example, as the report authors point out, Gene Editing pigs for resistance to PRRS disease, a disease associated with intensive farming systems, overlooks and risks perpetuating the root cause of the problem.

The first question all tech R&D should be asking is: Have we got the 'problem definition' right? Are we clear there isn't a mindset barrier or a farming or food system barrier before we assume that the barrier – and the 'silver bullet' - is tech?

Why farmer-led innovation matters

One of the key insights from this research is that farmers need to be co-designing tech from the 'problem definition' onwards, so that it will genuinely solve their field-level challenges and enhance their skills and experience, not seek to displace them.

Farmers know, better than anyone, the problems they face. What's more, they are great natural experimenters. They experiment all the time - trying new varieties, tinkering with equipment to fit their needs, and testing ideas to reduce costs, increase yields or improve soil health. This spirit of experimentation can only be good for agricultural research; bolstering robust academic investigation with hard-earned practical experience and innovative ideas from the ground-up.

However, farmer-led research is not commonplace in the UK. The public sector spends around £320 million on agricultural R&D with an estimated private sector spend of £496 million. But only 1% of the public funding in agricultural R&D is spent on farmer-led research.

This is why the Soil Association founded and leads Innovative Farmers, in partnership with LEAF (Linking Environment and Farming), Innovation for Agriculture and the Organic Research Centre. Innovative Farmers has connected farmers and scientists in designing over 100 field labs to date, ranging from sensors for tomatoes to targeting mastitis treatments in dairy cattle and alternative techniques to glyphosate for terminating cover crops. The collaboration is effective - the farmers ensure that the field lab is practical and is going to make sense to their business. The scientists give it some important rigour, help with a simple yet effective trial design and analyses that will ensure confidence in the findings.

Where next for AgroEcoTech?

It is clear from this initial research that effective governance could make all the difference in ensuring that technological innovation gets the 'problem definition' right and helps rather than hinders the system transition we need in food and farming for climate, nature and health.

Big questions remain, however, and we are launching this report to take the debate wider in the hope of beginning to answer these:

- How can we get tech governance right in a market economy? What are the levers?
- How can 'public money for public goods' be applied to Government-funded agri-food research in a way that leverages private finance too?
- How can 'problem definition' work better, so that green finance flows to tech where it is genuinely the best solution to accelerate an agroecological transition?

We want your help, as farmers, citizens and influencers, to define those 'problems' better. We'll be convening public sector research funders and tech leaders and we want to share your insights with them:

- What are the real 'problems' blocking the agroecology and sustainable diet transitions – from big to small - that are most in need of technological solutions?
- In your view, which emerging technologies could be the real game-changers? What would get your £1m?

Share your ideas: **#AgroEcoTech**

Executive Summary

Robotic milking systems have had increasingly wide uptake in dairies...

...with further opportunities for pest control, weeding, harvesting & irrigation

Alamy, © Small Robot Company

Aim and scope of the report

This report set out to investigate how technology might influence a transition to agroecological farming alongside a sustainable diet shift in the UK over the next ten years. The aim was to identify the technologies that could provide opportunities for farmers seeking to take up agroecological farming practices or reduce land pressure to enable agroecology. The report also seeks to identify which technologies risk inhibiting farmers from transitioning by incentivising and locking them into more intensive and less diverse forms of farming.

Given the uncertainty around these future opportunities and risks, a scenario analysis was constructed for each technology. Each analysis explored four possible scenarios showing the varying levels of support that a technology may have for agroecology.

It was clear from early in the project that the technologies themselves do not intrinsically support or restrict agroecology. Even those commonly thought to be contradictory to agroecology could conceivably offer some degree of benefit. It is instead the governance of these technologies that influences the role they will play. The structures and processes that influence decision making, if constructed appropriately, can promote funding, design, development, purchase, and adoption of technologies that align with a more agroecological farming system and restrict decisions that will do the opposite.

The final aim of this report was to identify the high-level principles for how agricultural technology governance should be structured to support agroecological transition.

The case for food and farming system redesign

The report is premised on a need to change the UK food and farming system. A system that is environmentally, socially, and economically, unsustainable.

Environmentally, agriculture is responsible for 10% of UK greenhouse gas (GHG) emissions, while our wider food system and its offshored land use change impacts are equivalent to 30% of UK consumption emissions (Audsley et al., 2009). Intensive farming and land use change driven by the food system is the largest contributor to biodiversity loss (IPBES, 2019); and agriculture is a major source of water and air pollution (BEIS, 2019; Dudley & Alexander, 2017). Socially, the cheap food paradigm has not improved access to nutritious food for healthy diets. The current food system plays a major role in the obesity crisis in the UK, which reduces the life expectancy of the two-thirds of adults in England that are now overweight. Economically, rising farm costs, grant dependence, and tightening profit margins have made farming financially vulnerable.

A report by the Institut du Développement Durable et des Relations Internationals (IDDRI) investigated the impact of a ten-year transition to agroecology in Europe (Poux & Aubert, 2018). IDDRI's report showed that agroecology could provide healthy diets, meet European food requirements, maintain export capacity, help restore biodiversity and lower agricultural GHG emissions by 45% compared to 2010. This report, by investigating the interaction between technology and agroecology, builds on IDDRI's work and aims to contribute to the understanding of agroecological transition.

Agroecology and Technology

Agroecology has been described as the ecology of food systems, encompassing ecological, economic, and social dimensions. In contrast to conventional agriculture, or even sustainably intensified or climate smart farming, agroecology considers the whole food system and its diverse impacts. FAO (2018) has defined ten elements of agroecology; of these diversity, synergies, efficiencies, resilience, and recycling all relate to the application of ecology to enhance the environmental sustainability of agriculture. The remaining five elements relate to the social aspect of agroecology. They are co-creation and sharing of knowledge, human and social values, culture and food traditions, responsible governance, circular and solidarity economy. Throughout the report these ten elements have been used as criteria to assess the relationship between technologies and agroecology.

Often agricultural technologies have not been developed to align with an integrated, sustainable, and agroecological food system. Instead, technologies have been designed to enhance reductive measures of performance, such as yield and profit. This has contributed to agricultural intensification. In turn, this has exacerbated a range of negative externalities that have been neglected and, therefore, allowed to grow.

However, burgeoning technologies may be more aligned with agroecological farming. Innovations are making technologies available that can accommodate the complexity of agroecological systems. The food system may be at a turning point where technology becomes capable of facilitating a form of agroecological production that is less labour intensive and hence more affordable and scalable. Where once technology triggered a transition to agricultural simplification, we may now see technology triggering increased diversity.

For this to be realised, however, it is important to review the opportunities and barriers that key technologies offer for an agroecological transition in the UK and assess how governance needs to be structured to facilitate these opportunities and remove the barriers. This is the aim of this report.

Technologies that represent the greatest potential opportunities for agroecology

This report cautiously proposes two groups of technologies that, with good governance, could provide the greatest support for an agroecological transition in the UK.

The first group includes technologies for remote sensing of environmental impact, big data analysis for environmental footprint accounting, and dynamic food procurement. These technologies can improve environmental monitoring and payments, reduce certification costs, enable green investment, strengthen local supply chains, and enhance transparency and traceability. Hence, these technologies can aid the creation of a food system that is more supportive of agroecology.

The second group relates to technologies that can support a more efficient and less labour-intensive form of agroecology. Smart agricultural technologies, robotics, and novel biological controls and inoculants make up this group. All have the potential to accelerate an agroecological transition by making it a more reliable and viable option for farmers of all scale. It is the first group of technologies that will create the demand for and stimulate investment in these technologies.

Technologies that demand tight governance to minimise risks

Whilst no technologies are completely incompatible with agroecology, some technologies pose greater risk and less potential benefit for agroecology.

Bioenergy production is perhaps the most conflicting technology. Incentives to produce bioenergy crops have frequently driven up pressure for land and food prices, stimulated habitat destruction, incentivised monoculture cropping and diverted valuable resources from farms. At scale, it is difficult to see how these technologies can be aligned with agroecology.

Other technologies pose a risk, as they may distract decision makers from systemic change. Genome editing is an example of this type of technology. The technology does provide some opportunities for agroecological transition through increased resilience. However, there is the risk that, without clear and precise regulation and governance, genome edited varieties distract actors from making systemic changes and instead enable intensified systems to be maintained.

The major risk for agroecology, however, relates not to one technology, but to the mentality that technology or input improvements will be the final solutions to problems in the food system. This was described by various actors in interviews and meetings throughout the project as a 'silver bullet' mentality. Examples include the idea that cellular meat will soon transform the meat industry, or that vertical farms will produce substantial percentages of urban food, or that genome edited seeds alone will expand yields and reduce impacts. This is not to say that these technologies will not play a role but too much confidence, investment, and attention risks distracting decision makers from more viable, cheaper, and more integrated interventions.

Key recommendations for agri-technology governance

Based on the research and consultation undertaken over the course of the project it was possible to identify key governance principles. These provide recommendations for how decision-making processes should be structured to enhance the role technology plays in supporting an agroecological transition in the UK. For a full and expanded list of these principles and recommendations see Section 6 of this report.

Principles and recommendations for participatory knowledge generation

1. Agroecology necessitates the development of knowledge sharing networks that facilitate peer-to-peer learning between farmers, and between actors and researchers operating across the supply chain. The public sector should provide funding and regulation that supports technological innovation that facilitates this learning through the development of smart farming networks.

2. Regulation must ensure that data collected on a farm must be made available to the farmer in an

accessible format. Farmers must have the rights to seek third party advice on the interpretation of this data.

3. Agricultural advice on the use of technology is too often left to companies with incentives to perpetuate conventional, input-intensive farming. Impartial advice rooted in good agroecological practice needs to be made available and promoted. The UK government should fund the development and dissemination of resources informing farmers about good agroecological practice. It should be mandated that all agricultural companies need to connect farmers to these resources when selling products. The aim is to avoid these companies controlling the advice given to farmers and to provide farmers with a way to validate the claims made by companies. Resources should also provide farmers with contacts where they can seek further impartial advice.

4. The UK education sector, and particularly universities, should encourage agroecological food system innovation. For example, competitions in engineering universities could encourage students to work collaboratively with agroecological farmers to design innovative robots.

5. Interdisciplinarity is key to the development of effective agricultural technology. Farmers must be involved in technology design, not just consulted on adoption. Development and testing should take place on real agroecological farms with real farmers. Public sector grants should necessitate farmer involvement and universities and research institutes should prioritise researcher-and-farmer collaboration.

6. Collaboration between academia and companies developing high profile disruptive technologies should be prioritised to improve the viability and validate claims. Attractive grants that necessitate collaboration and are considerate of issues surrounding intellectual property should be developed by the UK government.

Principles and recommendations for enhancing accessibility and equity

7. Access to sustainability enhancing technology, and particularly data gathering solutions, should be maximised across all scales of agriculture. Regulation should be restructured, and incentives put in place to encourage companies to develop innovative modular, flexible, interoperable technologies accessible through rental and service-based schemes. This will increase access to cutting edge agricultural technologies.

8. All actors should have the right to repair and adapt technology that they own. Standards and regulations should enhance repairability and interoperability. Modularity and adaptability should be encouraged.

Principles and recommendations for enhancing accountability and transparency

9. Technology should be adapted to accommodate the diversity of good agroecological systems, agricultural systems should not be adapted for technology. The UK government should appoint or identify an interdisciplinary board to use the defined core features of good agroecological systems to create a framework for reviewing new crop varieties and public investment in technologies. This framework should be used to guide development, policies, grants, subsidies, and investments.

10. The same interdisciplinary board should be appointed by the government to develop an integrated form of cost-benefit analysis incorporating predicted environmental and social aspects. This analysis tool should be factored into public and private investment decisions in the food sector. Investments found to have substantial predicted environmental and social costs should be restricted. This integrated cost-benefit analysis would also reveal opportunities that could have substantial environmental and social benefits but have low market value. The UK government should establish mechanisms to support such opportunities.

11. The UK government should enforce the development and integration of standardised, thorough, and transparent lifecycle analysis across all large industries and encourage uptake in developing sectors. The lifecycle analysis procedures should be developed by third-party interdisciplinary bodies and not by the industry.

12. Regulation should ensure reviews of new crop varieties, key performance indicators of public sector investment, and life cycle analysis of technologies are made publicly available and communicated in an accessible manner. This should give the public a chance to provide feedback, which should be considered during decision making.

Farmers' voices

A group of farmers and actors familiar with agroecology was convened for a co-design workshop. The aim of the workshop was to allow the participants to discuss the technologies explored in this report and develop their own principles for governance of these technologies. Findings from the workshop largely echoed those of the wider report. For a more extensive summary of the workshop see Appendix 1.

The participants generally saw technology as one component of a broader approach to innovation

Alamy

for agroecology that gave equal emphasis to management and practice innovation. The widely held view was that technology should fit into the agroecological system and enhance the farmers' ability to manage natural systems by reducing the most arduous tasks, enhancing knowledge generation and sharing, and enabling them to validate and be rewarded for the public goods they provide through good agroecological management. Technologies like digital food hubs and dynamic food procurement were welcomed as opportunities to shorten supply chains and connect farmers with new local markets.

Participants were most concerned with the continued mindset that technology was going to completely solve problems in the agricultural systems. They were concerned that this mentality would suppress traditional knowledge forms and sharing, deskill the sector, divert investment from more practical and less costly solutions, and lock farmers into high-cost intensive farm management. Participants were also concerned that a lack of control over automation and data could leave them increasingly exposed to risks they would not be able to manage.

Key unanswered questions

This is a high-level report providing an overview of the technologies and the major risks and opportunities. Many questions remain unanswered for each of the technologies and work needs to be undertaken to explore the complex interactions between these technologies and agroecology.

Additionally, each of the principles should be developed further and recommendations for operationalisation provided. Work is needed to develop frameworks for reviewing technology governance and investment; this will help with monitoring and guiding governance towards greater support of agroecology. The indicators suggested in Section 7 of this report provide some initial thinking on this. Future indicators and frameworks must help decision makers review the broad spectrum of public goods and impacts that a technology can provide. This would enable decision makers to shift support, regulation, and investment towards technologies that supply a wider range of services than just increased yield and profit. If this is not achieved, there is a risk of further locking farmers into unsustainable intensive farming systems; perpetuating and creating unintended externalities; increasing food system fragility; and reducing public health and wellbeing.

Technology can play a positive role in a transition to agroecology in the UK. It can make agroecology a more viable, less risky, and less arduous form of farming. But, this will only happen if technology is designed and developed for agroecological systems. To make this happen, governance is needed that creates greater understanding of agroecology, more collaboration and knowledge sharing, and establishes regulations and incentives that shift technology development and investment towards greater provision of public goods.

1. Introduction

1.1 Background to Agroecology

Agroecology is a concept that was first used in the 1930s by Bensin (Wezel et al., 2009), a Russian agronomist, to describe the application of ecological methods to commercial crop plants. This definition is narrower than others but remains in use. Through this lens, agroecology is a scientific discipline that applies ecological concepts to study, design, manage and evaluate productive and resource-conserving agricultural systems (Altieri, 1989).

In contrast to conventional agriculture, or even sustainably intensified farming, agroecological systems depend on diversity. As in ecosystems, each element of an agroecological system fills a niche and provides a function. The symbiosis between the diverse components of an agroecosystem supports the provision and use of ecosystem services. This minimises externalities, maintains productivity and reduces reliance on external inputs. Reduced reliance on external inputs aligns agroecological theory and practice with organic farming. Organic standards and regulations prohibit organic farmers from using most chemical inputs and many use agroecological techniques to replace these inputs.

Agroecological systems provide a wider range of ecosystem services than conventional agriculture (Boeraeve et al., 2020). They have the potential to enhance soil health, carbon sequestration, water quality, and flood reduction. FAO (2018) has defined ten elements of agroecology; of these diversity, synergies, efficiencies, resilience, and recycling all relate to the application of ecology to agriculture.

A common critique of agroecology is that it is incapable of producing enough food for the world. However, whilst agroecological yields are generally lower than on conventional farms, there is growing evidence that these systems can close the yield gap between organic and conventional production, whilst enhancing environmental, economic, and social sustainability. Jules Pretty (2020) has done extensive work validating the yield increases agroecology can provide, particularly in poor nations. He reports average yield increases of 79% across 57 countries with substantial reductions to environmental impacts and cost. However, whether similar results can be achieved across the technology-intensive systems of the United Kingdom (UK) is questionable. A report by the Institut du Développement Durable et des Relations Internationales (IDDRI), however, has found that a transition to agroecology across Europe can provide adequate healthy food for Europeans, despite yield reductions.

More recent definitions of agroecology go beyond the farm level and take a wider, more integrated stance. Francis et al. (2003) describes agroecology as the ecology of food systems; this definition encompasses ecological, economic, and social dimensions. It accounts for how food systems impact public health, either through environmental impacts or through inequitable access to nutrition; it integrates the environmental impact of globalised food chains; and it factors in the risk of urban isolation from nature and misunderstandings of its value. Modern definitions have come to incorporate not just the study of the interaction between ecology and food production, but also the relationship between those systems and humans. This more social arm of agroecology is concerned with food security, sovereignty, and autonomy. It calls for greater localisation and community control of land, water, and agrobiodiversity. The remaining five elements of agroecology, as defined by FAO (2018), relate to this social side of agroecology. They are co-creation and sharing of knowledge, human and social values, culture and food traditions, responsible governance, circular and solidarity economy.

1.2 Agroecology and technology

To date, diverse, agroecological systems have not been well served by the application of labour reducing technologies. These technologies, such as combine harvesters, tractors, and pesticides, necessitate system standardisation. Standardisation is at odds with the core tenets of agroecology. The misalignment of technology with agroecological farms, alongside the externalisation of environmental costs by conventional farms, has left these farms struggling to compete with the economics of conventional production. Whilst farm standardisation has become normalised, agroecological farming, which was once common, has become a niche form of food production in the UK, reserved for those who can afford the higher price tag. In turn, the food system has evolved with this shift toward large scale standardisation. Crops have been bred for standardisation; supply chains have become increasingly centralised and suited to the delivery of large quantities of singular commodities; processing and preservation have become necessary to utilise mass production of commodity crops; the wasting of cheap food has become routinised; in so many ways our food system has adapted to technology.

This systemic standardisation, facilitated by technology, has had numerous social impacts. Europe has seen high levels of farm abandonment, particularly for small to medium-size farms and those in less productive areas (MacDonald et al., 2000). The drive for industrialisation and intensification has reduced the viability of these farms. This trend risks eroding traditional rural cultures, knowledge, seed and livestock varieties and practices, many of which are now being shown to hold considerable value for sustainable food production. Agricultural intensification and urbanisation have driven a supply of highly processed foods contributing to a rise in non-communicable diseases. Many people now find themselves more separated from the natural world than ever before, and less capable of making informed decisions about sustainable consumption or accessing nutrient-rich foods. These impacts of agricultural technology conflict with the social elements of agroecology.

The incompatibility of technology with agroecology, however, may be changing. Innovations are making technologies available that can accommodate the complexity of agroecological systems. The food system may be at a turning point where technology becomes capable of facilitating a form of agroecological production that is less labour intensive and hence more affordable and scalable. Where once technology triggered a transition to agricultural simplification, we may now see technology triggering increased diversity. For this to be realised, however, it is important **to review the opportunities and barriers that key technologies offer for an agroecological transition in the UK and assess how governance needs to be structured to facilitate these opportunities and remove the barriers**. This is the aim of this report.

1.3 Report Structure

For this report, eleven major types of technologies have been identified based on the likelihood that they will substantially influence a transition towards agroecology. An advisory panel of agricultural and technological experts supported the identification of technologies for review. The report groups these technologies into four sections: production technologies (**Section 2**), technologies for impact monitoring (**Section 3**), supply chain technologies (**Section 4**), and technologies influencing agricultural demand (**Section 5**).

The technologies within each section have been reviewed drawing on information from peer-reviewed meta-analysis, studies, media, and expert advice. Each review briefly introduces the technology and then identifies the main opportunities and risks each technology poses for agroecological transition.

Using the collated information, we then construct a scenario analysis for each technology. This presents four scenarios representing how the technology may support or restrict the ecological and social elements that are core to agroecology. This scenario analysis is presented in a simple table and a traffic light system is used to indicate the degree to which each scenario supports an agroecological transition.

In **Section 6** the technological reviews have then been used to define common governance principles for enhancing the role technology will play in agroecological transition over the coming decade. In **Section 7**, we propose indicators that could be used to validate whether the defined governance principles are being met. Finally, the report closes with a discussion in **Section 8** in which we reflect upon the findings, what they mean for AgroEcoTech governance and make some recommendations for future research.

2. Production Technologies

2.1 Smart Agriculture

For this report, we define smart agriculture as the use of information and communication technologies (ICT) to enhance agricultural management. Technologies that include the use of hyperspectral cameras, sensors, geographic information system (GIS), modelling, big data, and machine learning.

These technologies, especially when combined, have the potential to form networks enabling almost continuous farm monitoring. Numerous variables can be monitored including growth rate, biological activity, moisture content, nutrient availability, disease and pest damage, and livestock location. Machine learning, artificial intelligence, and modelling can then be used to triangulate this data against weather patterns, market trends and performance of other farms to supply usable insights to the land manager.

It is predicted that over the coming years ICT will be integrated into agricultural management to a far greater extent. The resulting development of smart information networks will enable more precise agricultural management, enhancing resource use efficiency and performance, reducing costs, risks, and labour requirements. Information gathered will support the application of agricultural robotics. These autonomous technologies can use the data to inform when managements such as pest control, weeding, harvesting, and irrigation are necessary.

The Current State of the Technology

Currently, smart agriculture is most associated with large scale, precision farming, predominantly spraying. Technologies such as real-time kinematic (RTK) positioning enable the highly accurate application of chemicals. High costs, however, mean access to smart technology is restricted to big, industrialised farms, where economies of scale make the technologies a worthwhile investment. There is a need to develop lower-cost, flexible smart technologies for smaller and more diverse farms.

Smart technology and data gathering are also common in research and academia. Considerable amounts of data are collected on agricultural systems using a plethora of technologies across a range of geographical scales. However, this information is rarely made accessible to actors outside of the scientific community (Raghavan et al., 2016), either because of the use of technical language or paywalls. Accessibility and usability need to be prioritised to a much greater extent.

Opportunities for Agroecology

Agroecology is a context-specific approach. Management must accommodate local climates, markets, soil type, and species. This means knowledge, techniques and crop combinations developed in one area may not be viable elsewhere. Developing resilient agroecological systems requires considerable and varied knowledge. It can take individuals decades to gather and apply this knowledge to create functional agroecosystems in a specific context; this is a major bottleneck for agroecological transition (Raghavan et al., 2016). Smart agriculture can help accelerate this process, by efficiently collecting, aggregating, and interpreting multiple data sets. If effectively designed, this can provide land managers with practical insights into how to develop

CASE STUDY

Smart Technology in Livestock Farming

A research project by Barriuso et al. (2018) demonstrated the value of smart agricultural networks in livestock farming.

They developed a wireless network using a variety of sensors to monitor cattle feeding, location, motion, and temperature. Data collected was communicated to the farmer through a television, as this was the preferred method stated by the farmers. The network provided farmers with real time information about changes in the herds' behaviours including feeding patterns, escape, theft, oestrus, and calving.

The aim of this network was to save the farmers time following and observing cattle; to increase the productivity of the farm; and to reduce costs and risky situations. The farmers highlighted labour detection as a particularly valuable aspect of the network; it enabled them to go into the field and assist the cows only when it was necessary. This meant the farmers could work more effectively and reduce the risk of problems occurring unobserved. The system also detected feeding anomalies; the farmers said this information made their work more comfortable as they had to spend less time observing the cattle.

Crucial to the success of this project was its development with real farmers. Feedback from farmers informed the researchers that the preferred means of communicating the information was through the television, hence they adapted the system to this method of display. Farmers also stated that the amount of data initially communicated was overwhelming; the researchers responded by reducing the number of variables communicated. This type of iterative and collaborative research is paramount for the development of effective AgroEcoTech.

A commercial example of this kind of sensor technology is Afimilk (https://www.afimilk.com/). The company sells collars and leg sensors for cows. This provides farmers with insights on health issues, digestion, milking, oestrus, and calving.

From an agroecological perspective, this type of technology could enable more extensive grazing. This is because farmers would be able to let cattle graze more freely. It may also enable farmers to diversify their productions as they would have more time to integrate different elements into their agricultural systems.

On the other hand, there are risks that this technology could encourage increased intensification. Feed monitoring may be less suitable for grazing cattle as it is harder to track their feeding patterns. Additionally, high costs and labour reducing technologies may enable and incentivise farmers to increase the size of their heard to offset the cost of investment. This would conflict with agroecological low intensity grazing.

Scenario Analysis of Smart Agriculture

	Consolidated control	Equitable food system
Agroecological diverse food production	Modular sensors are suitable for use in diverse agroecological systems. However, high cost and high levels of expertise are needed to operate the technology. This restricts access to the larger scale and more profitable farms.	Modular sensors applicable to a wide variety of cropping systems are available and applicable to all scales of agriculture. Sensors are flexible to system heterogeneity and interoperable with a wide range of technologies and practices. Sensors are developed in collaboration with farmers and designed for accessibility and usability. Farmers are incentivised to share information gathered across a network to enhance agroecological knowledge. Sensors, where appropriate, are available through rental and shared ownership schemes.
Intensive agriculture	Sensors are developed and commercialised by large agricultural technology and seed companies. The technologies are only sold as components of technologies that are suited to large, simplified, intensive agricultural systems. Data gathered and processed is used to recommend farmers to use conventional products also sold by the companies. This locks users into intensive farming.	Sensors are adapted for conventional practices such as spraying but made accessible to a variety of farmers through lower costs and rental and service models.

regionally adapted agroecological systems.

This kind of smart agriculture would differ from that applied to conventional systems. Conventional smart systems generally work with one-size-fits-all solutions that optimise the precise application of resources in a highly regulated way. In contrast, smart agroecological systems should integrate diversity, context-sensitivity, adaptability, and interoperability (Wittman et al., 2020). These systems can aid the planning, building, and maintaining of sustainable agroecosystems (Raghavan et al., 2016).

Smart agroecology will benefit from high levels of farmer participation and open-source data sharing. The accuracy of data collected by an individual farmer may be lower and have little relevance to other farmers, even those in the same region. However, validity will increase as more farmers share data; this has been called the "Wisdom of Crowds" principle (Wittman et al., 2020). It can also be referred to as a positive network externality; as more actors participate in the network, machine learning will increase the accuracy of modelling and hence the validity of recommendations.

Risks for Agroecology

Smart and precision agriculture has traditionally been entwined with conventional management. The precise spraying of pesticides is one example. Whilst this helps reduce input use and drift, it does not enhance in-field functional biodiversity nor align with agroecology. There is a risk that smart agriculture continues to be developed for conventional application methods. Sensors might be developed and patented by agrochemical companies; guidance limited to recommending the amounts of inputs to use; and data collected and utilised by the companies. This would limit the flexibility of farmers who invest in a smart agricultural approach and narrow their understanding of land management, whilst locking them into input dependence.

2.2 Robotics

Robotics has the potential to transform the agricultural sector in a variety of ways. The most cited is the potential to reduce the need for arduous, time-intensive, and dangerous jobs.

Whilst conventional agricultural technology has reduced the labour requirements of certain standardised tasks such as tilling, and cereal harvesting; robotics has the potential to do the same for more complex, tactile, and heterogeneous jobs.

In a white paper on the topic of agricultural robotics, the UK Robotics and Autonomous Systems Network (UKRAS) (2018) present a vision for the future where agriculture is supported by fleets of smart, flexible, robust, compliant, interconnected robots that work alongside humans across the entire food chain. In this vision, autonomous technologies remove the need for arduous and unpleasant work, making the agricultural sector more attractive to skilled workers and graduates. Humans work collaboratively alongside robots facilitating effective and sustainable management of agricultural systems. These technologies remove the need for dull, and dangerous tasks, improving the quality of life and safety of those in the food sector.

Robots have the potential to automate a huge number of tasks. Soft robotics and advances in sensors may unlock automated fruit and vegetable harvesting. Camera guided hoes, precision sprays, and lasers will improve the sustainability and efficiency of weed management. Automated lightweight, electrical vehicles will reduce fuel consumption and lower the chance of injury due to human and machine interaction. Drones can seed, spray, and gather information with unprecedented precision and with no soil compaction. Automated herding, milking, feeding, cleaning, and butchering technologies have great potential for improving the efficiency, welfare, health, and safety of the livestock sector. "Multi-modal" platforms that combine ground-based and aerial vehicles have the potential to provide enhanced benefits, enabling multiple tasks to be undertaken simultaneously, and enabling human operators to observe and manage systems in a highly informed, precise, and efficient manner.

The current state of the technology

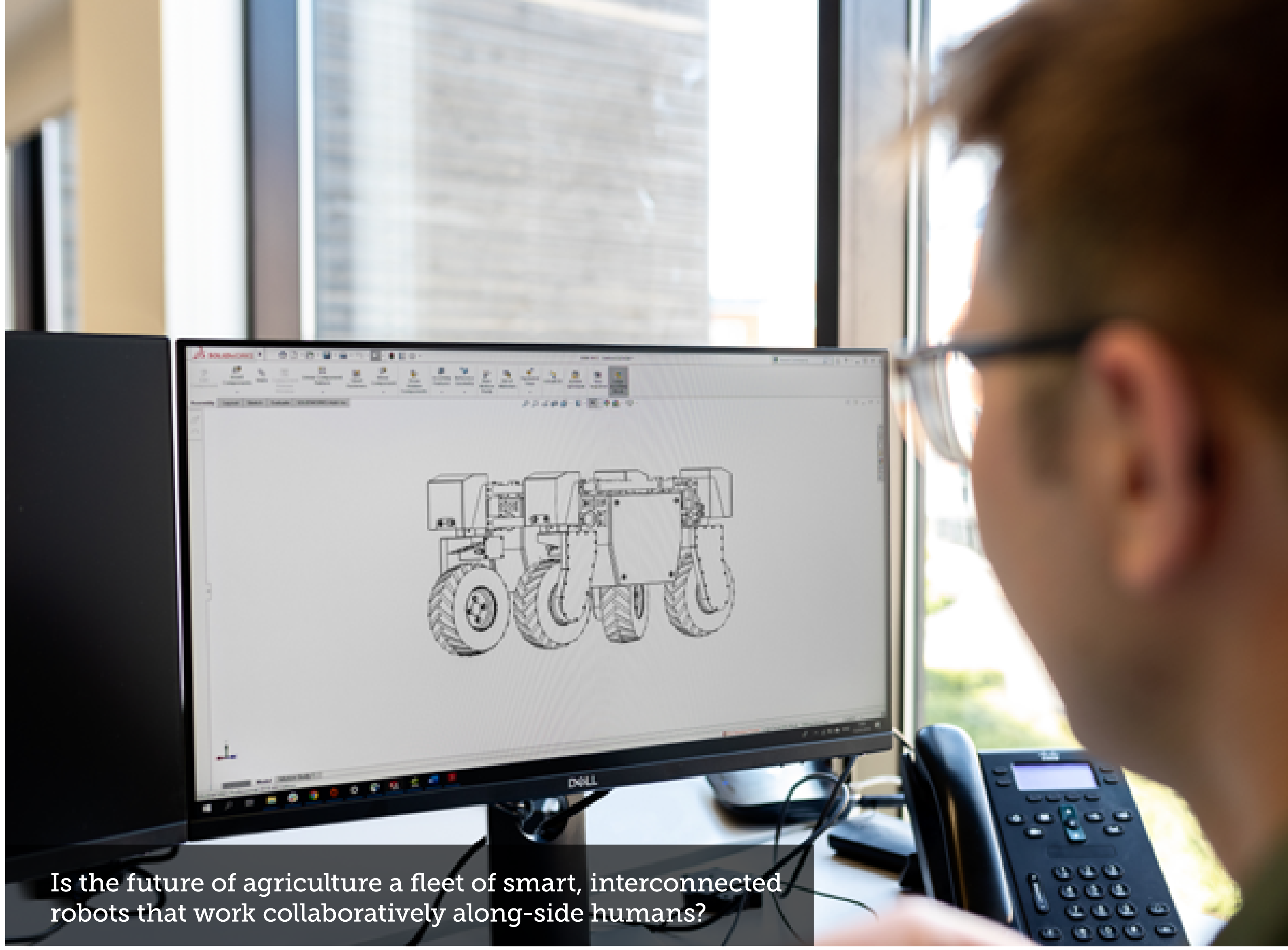
The agricultural robotics sector is still embryonic. Few examples of market-ready products exist. Robotic milking is one example of an increasingly widely integrated automated technology. However, most technologies are at the research or start-up phase.

Prominent research projects, such as the 'Hands Free Hectare'[1] have demonstrated the potential of autonomous farm technology and are now applying these technologies to larger areas, attempting to demonstrate the technologies viability for UK agriculture.

In the private sector companies such as 'Naio Technologies'[2] are now reaching commercialisation, with three small weeding robots on the market. In the UK, the 'Small Robot Company'[3] is receiving considerable attention and currently demonstrating and trialling its fleet of monitoring, mapping, and weeding robots. Research has found that weeding robots have the potential to reduce weed

1 https://www.handsfreehectare.com/
2 https://www.naio-technologies.com/en/
3 https://www.smallrobotcompany.com/

Male mechanical engineer designs agricultural robots © This is Engineering/Flickr, Innovative Farmers


Is the future of agriculture a fleet of smart, interconnected robots that work collaboratively along-side humans?


Growers supported by Innovative Farmers are testing water balance sensors on greenhouse tomatoes to see if they can optimise their growing environment and reduce loss from disease.

CASE STUDY

The Economics of Agricultural Robotics

The economics is one of the major factors that will influence the uptake of robotics in the agricultural sector. Generally, farmers will not invest in innovative and unfamiliar technology if there is not clear evidence that it will improve their economic viability.

Additionally, the scale of investment required will influence which kinds of farmers can access these technologies. Hence, it is important to validate the financial impact of these technologies.

Lowenberg-DeBoer et al. (2019) produced a rigorous economic analysis of the impact of swarm robotics on UK arable farms. This analysis was based on data collected from the 'Hands Free Hectare' project. Hence, it is one of the only economic studies of automation based on real field data. They calculated that robotics could enable grain farmers to become profitable at smaller scales due to reduced labour and equipment investment. This could be achieved with lower environmental impact and greater soil fertility on smaller and more irregularly shaped fields. It was posited that this could give farmers greater scope to diversify their cropping, integrate livestock into rotation, and enhance habitat provisioning.

Whilst this study is grounded in field data, it does not factor in costs of commercial robots, regulatory barriers, or labour needed to supervise the robots. This means there is considerable uncertainty surrounding the findings.

In fact, a case study by Lampridi et al. (2019) modelled the impact of automated light cultivation on farm economics and produced contrasting results. Their assessment found that production costs were greater for the automated system due to low efficiency and time spent recharging. Moreover, the costs were greater for smaller farms but diminished with increased scale. From this perspective, automation would increase pressure for farmers to scale up to absorb the costs of automated equipment. However, if human labour could be completely removed from the activity, then the robotic system would become more economic than the conventional, even at small scale. This is not currently possible though.

These varied assessments of agricultural automation demonstrate the uncertainty surrounding the sector. It is not yet clear which forms of automation will be most economically viable, how they will impact the structure of farms, and how regulation will affect their application. It is imperative that research continues to look at the systemic impacts of robotics to better comprehend how they may restructure future agricultural systems.

chemical use by 80-90% and weeding operation costs by 90%[4].

Over the last few years, the increased availability of cheap, lightweight, and smart components alongside new fabrication techniques such as 3D printers have supported the development of robotics and decoupled manufacturing and innovation from mainstream processes and supply chains. In the UK, covid 19 travel restrictions and Brexit have thrown into doubt the reliability of international labour that has traditionally supported much of the agricultural sector. This has stimulated increased interest in agricultural robotics.

Regulation is a considerable barrier to the development of the sector. Standards and regulations around automation in the agricultural sector are lacking and many companies have found it difficult to gain permission for the sale and use of their technologies. This is largely due to the safety concerns around unmanned vehicles in the countryside. There is a need for a reappraisal of the legislation surrounding automation to unlock the potential of these technologies.

Opportunities for Agroecology

Small robots have the potential to operate in more heterogeneous systems, suiting them to agroecological practices such as strip agriculture and agroforestry. The mechanisation and automation of more complex systems may make them more viable at scale and more competitive with conventional monocultures. Robotics could unlock highly diversified mid to large scale farms that have previously been unviable due to their incompatibility with conventional technology.

Lightweight robots have the potential to drastically reduce soil compaction. This would likely reduce the need for frequent tillage, enhancing soil health and mycorrhizal activity. This could improve the efficiency of plant nutrient uptake helping farmers reduce their reliance on artificial fertilisers. Additionally, reduced tillage would improve the carbon content of soils. Drones and other lightweight robots may be able to sow directly under crops, reducing the time that soil is left bare. This would enable farmers to reduce soil erosion, limit compaction, and enhance water retention.

In recent years mechanical methods of weeding have not been viable at scale, either due to the labour costs of manual weeding or the inaccuracy of mechanical methods. Autonomous vehicles, however, can work more precisely over much longer periods. This suits them to non-chemical weeding. This would benefit ecosystem functioning, reinforcing good agroecological production by enhancing biological pest control and pollination.

Automation in the livestock industry may make extensive farming less arduous, more cost-effective, safer, and reduce the risk of contamination in abattoirs. Technologies that automate the herding of extensively grazed animal have already been commercialised. The reduced need for strenuous activity may open the agricultural sector to a greater diversity of workers. Elderly and disabled citizens may be able to contribute more effectively to sustainable land management.

Finally, new automated agricultural services may make efficiency improving technologies more accessible to a wider range of farmers. In China, drone rental can be requested through an app. These kinds of innovative rental models, enabled by small autonomous flexible technology, could make the benefits of precision farming accessible to farmers who have traditionally not been able to afford technologies.

4 https://research.qut.edu.au/future-farming/projects/robot-platform-design-agbot-ii-a-new-generation-tool-for- robotic-site-specific-crop-and-weed-management/

Risks for Agroecology

There are also potential risks associated with robotics. These technologies may reduce flexibility in agriculture. Farmers may be incapable of or legally restricted from altering the functionality of a certain technology. If this technology is designed for a restricted task, that depends on a certain degree of system simplification, agroecological transition may be restricted. If robots are designed and promoted for the maintenance of monoculture production, this is a likely outcome and may leave farmers invested in and locked into this form of production.

Robotics may unlock farming in less accessible areas, where inaccessibility for large machinery once prohibited productivity (UKRAS, 2018). Whilst this could have significant benefits for farmers in these areas and could increase potential food production, this must not lead to the degradation of once sustainable systems through over intensification.

Finally, it should be intended that robots are designed to facilitate good agricultural practice. Agricultural practice should not be designed to facilitate the use of robotics. Monoculture systems have developed to a certain extent to accommodate large scale agriculture machinery, with unintended consequences. Robotics should not emulate this narrative. In the UKRAS report, the authors mention the need to breed crop varieties suited to robotic harvesting. This is an example of how automation could begin to dictate how agroecosystems are structured. Such approaches should be thoroughly and critically evaluated as it may be difficult to identify the knock-on effects, before they become locked in.

2.3 Genome Editing

'Genome engineering (or genome editing) can generally be defined as the targeted modification of DNA within living organisms' (Baltes et al., 2017).

This covers a wide range of genetic modification techniques and products that alter the genetic makeup of organisms in a variety of ways and to greater and lesser extents. The resultant organisms are often called genetically modified organisms (GMOs).

In 2015, the breakthrough clustered regularly interspaced short palindromic repeats (CRISPR/Cas9) system was developed enabling genome editing to be undertaken with increased precision and efficiency. CRISPR/Cas9 is one of a host of gene editing techniques including meganucleases, zinc finger nucleases (ZFNs), and transcription activator-like effector-based nucleases (TALEN).

Genome editing (GE) techniques can be used to edit the DNA of organisms in a variety of ways. Single Nucleotide Polymorphisms (SNPs) cause a change in just a single nucleotide. Indeles are small deletions or insertions typically less than 100 nucleotides. Large deletions remove larger sequences of DNA whilst insertions involve the targeted addition of DNA sequences into predetermined locations within a genome.

Over the last decade, numerous products and research projects have been produced using these technologies. In crop science, broadly speaking, the aim is to enhance agricultural performance. This can be achieved by editing to

Scenario Analysis of Agricultural Robotics

	Consolidated control	Equitable food system
Agroecological diverse food production	Flexible swarm robots can farm diverse systems but only at a high scale due to cost and the need for specialised training, consultation, certification, and staff. Large farms become more environmentally sustainable and efficient but outcompete small to medium scale farms that cannot afford automation.	Robots are designed for adaptability, heterogeneity, and minimal soil impact. Robots are not dependent on the use of chemical inputs. Alternative ownership models such as rental and collective ownership are available and incentivised through policy. Robots have been developed collaboratively with engineers, designers, researchers, and agroecological farmers, on agroecological farms.
Intensive agriculture	Automation is absorbed into the conventional approach. Spraying, tillage, and fertiliser application are all automated. Less staff are needed on farms, whilst resources are used more efficiently exacerbating consolidated land ownership and rural depopulation. Farmers do not own the automated equipment and do not have the rights to adapt or repair it. Automation further distances farmers and the public from natural cycles and de-skills farming.	Innovative ownership models, rental, and service schemes make robotics accessible to a wide range of farming. This helps lower the costs of farming and removes the need for large investments in technology. Lowering the labour and costs of farming helps diversify the sector bringing in specialists in a variety of fields and allowing less physically able actors to contribute to farming. However, the technology is designed inflexibly. It is tied to the use of chemicals, suited to relatively standardised systems, and does not encourage farmers to take up a more reflective and nature-friendly approach. This leads to a more equitable but intensive food system.

increase yields, increase resistance to plant pathogens, enhance weed management, increase resistance to abiotic stress and enhance the nutritional composition and processability of produce. The specific methods used to achieve these trait alterations differ greatly. This makes the impacts of the technologies difficult to generalise.

The report by the National Academies of Science, Engineering and Medicine in the United States (2016) concludes that there is no substantiated evidence of a difference in risk between gene edited and conventionally bred crops. The authors recommend that there is a need to investigate future regulation and standard that review new crop varieties based on the strain's characteristics rather than the process by which it was developed.

The Current State of the Technology

The current state of GE technology in the UK has been impeded more by regulatory constraints than technical ones. EU regulation, and therefore UK regulation, has to date restricted the use of GE in agriculture. Having left the EU, the Department for Environment, Food and Rural Affairs (DEFRA) in the UK is seeking consultation on the future regulations of these technologies[5]. This consultation will predominantly focus on whether to free from current GE regulations, the use of GE to induce changes that "could have been introduced by traditional breeding". The consultation also seeks comment on just what changes should qualify as meeting this. The broadest possibility are those changes which involve the transfer of genes between members of the same species, known as cisgenesis.

The Dutch government and various other actors support the use of CRISPR/Cas9 when these techniques are used within the classical breeding gene pool (EFSA, 2012; Lotz et al., 2020 Sprink et al., 2016). They argue that regulatory decisions should be made on a crop-by-crop basis based on the traits and predicted impacts of the crop. This is likely to be the rationale behind DEFRA's review of the regulation restricting the use of this method. However, developing standard, regulations, and tests that can validate an absence of foreign genetic material and effectively assess the highly complex systemic impacts of these new varieties is a considerable challenge.

Worldwide GMOs have been grown for over fifteen years and across 1.25-billion-hectares. The accumulated empirical evidence suggests that this has been relatively safe and that the benefits of these crops outweigh the costs and have disproportionality favoured poorer farmers (Barrows et al., 2014; Zilberman et al., 2018). Studies have also found evidence that GMOs can play a role in reducing pesticide and herbicide use and increasing uptake of no- and low-tillage farming (Klümper and Qaim, 2014; Smyth et al., 2011; Zilberman et al., 2018).

The issue is that most of this evidence has been collected on conventional, industrialised farms where short term significant improvements are more easily achieved. Similar impacts on organic and agroecological farms are more difficult and less investigated. Moreover, whilst incremental reductions to pesticide use in the short term can be found, it is difficult to say whether these improvements can be increased or even sustained. In fact, it is likely that they plateau, allowing farmers to reach a level of sustainable intensification, but failing to enable a full transition to agroecological production. For example, herbicide resistant crops will enable a farmer to use these chemicals more efficiently, but they cannot completely remove the reliance, nor do they circumvent the major issue of resistance developing in targeted weeds.

GE techniques have been used to enhance a wide range of traits. Lotz et al., (2020), describe GE blight-resistant potatoes, rice resistant to Xanthomonas oryzae pv. oryzae (Xoo), and various transgenic crops which are more resistant to pests due to increased production of Bacillus thuringiensis (Bt) protein. Baltes et al. (2017) identify various strains created to overcome certain barriers to agricultural production including a rice strain with three genes knocked out enabling increased grain size and weight of up to 30%; a tomato strain created for more commercially efficient flowering time; and a variety of crops edited for glyphosate resistance.

Evidence collected from farms growing GE varieties has not shown a long-term reduction in crop genetic diversity (Krishna et al., 2015). In fact, it is claimed that genome editing technologies may even have the potential to enhance crop diversity by enabling cheap, targeted, and efficient insertion of select traits into a diversity of crop varieties. This may enable the reintroduction of traditional seed varieties that were previously abandoned because of pest damage (Barrows et al., 2014). However, given the need for biotechnology companies to maximise profits and cover the considerable costs of crop development, they are more likely to drive for fewer varieties with higher potential for yield enhancement, than for a diversity of more ecologically aligned strains. This could exacerbate the proliferation of monoculture farming, rather than enable increased heterogeneity.

In addition, the need for GE companies to protect their intellectual property rights means there is a legitimate concern that GE crops will suppress farmers capacity to retain their own seed stocks and maintain resilient and diverse land races. Promotion, development, and reliance of GE varieties developed for enhanced yield could stimulate agricultural intensification and increase system fragility. There is a need for greater investigation of regulations and governance that can avoid these systemic impacts. Currently, this risk is being largely passed over as an area of investigation.

Another concern is that traits and genes might spread from GMOs into surrounding ecosystems. This is of particular concern if genes enhancing resilience were to be passed to 'weed' species. This risk is generally low since commercial crops are usually genetically distant from their wild relatives, but it has occurred (Zilberman et al., 2018). In cases where this is deemed to be a risk, laws have been put in place to prevent GE crops being grown. There is a need to continue assessing this threat and the effectiveness of these measures.

Opportunities for Agroecology

Lotz et al. (2020), present a case for how gene editing can enable a transition to agroecology. They claim that gene editing for improved pest resistance can reduce farmer dependence on insecticides, fungicides, and herbicides. Bt varieties have also been shown to reduce impact on non-target organisms as they only impact pests consuming the crops (Zilberman et al., 2018). Reduced spraying means less damage to predator species. This can enhance the role predators play in biological pest control, particularly when predator habitat is intentionally provided.

Pest, disease, and herbicide resistant varieties have been shown to increase the viability of low- and no-tillage farming (Smyth et al., 2011; Zilberman et al., 2018). By enabling farmers to maintain more continuous soil cover these varieties can, therefore, enhance soil health and ecosystem functioning. These examples demonstrate how

5 https://consult.defra.gov.uk/agri-food-chain-directorate/the-regulation-of-genetic-technologies/

GE varieties might enable farmers to transition towards more agroecological growing methods. In this context, gene editing technologies can be viewed as a kind of bridge towards agroecological methods. In practice, low- and no-tillage farming often occurs without wider agroecological farm system changes. Gene editing may facilitate this pattern on a much broader scale, unless agroecological principles, for example around diverse cropping, are encouraged at the same time.

Indeed, it may be that a complete rejection of gene editing technologies by the proponents of agroecology could drive farmers further towards an intensive approach. Rejecting the technology may leave the agroecological community less able to influence the implementation and regulation of gene edited strains. Rejection may lead agroecology to be viewed as impractical by farmers who wish to use gene edited seeds to reduce their dependence on chemicals in the short term but otherwise align with agroecological principles. Acceptance of certain forms of genetic engineering may give those promoting agroecological methods more scope to influence which strains are permitted, and how they can be used as transition technologies.Several meta-reviews, such as that by the National Academies of Science, Engineering and Medicine in the United States (2016), have concluded that the implementation of GE crops has been shown to generally benefit farmers and product market chain, provided implementation encompasses good agricultural practice. This statement is contingent on what is deemed to be good agricultural practice. Failure to ensure gene edited strains align with agroecological systems may risk perpetuating lock-ins to alternative systems.

This leads to a broader question about how gene editing technologies should be governed. How should society decide what is a permissible use of gene editing technologies? And how should this be regulated? This is a difficult decision and one that will be exacerbated by polarisation in the debate and misconception in the scale, type, and cause of risk and opportunity. This, however, must not be used as a rationale to exclude the public from the conversation. The debate must not become siloed into the scientific community but must be interdisciplinary and participatory. Implementation of these technologies must be sensitive to more than just economic impacts, but also acknowledge local biophysical conditions and social, institutional, political, and cultural contexts (Stirling, A. 2015, Lotz et al., 2020).

The issue is that concerns voiced around the systemic risks of these technologies tend to come from those who largely reject them. This is the polar opposite to those that support these technologies, who largely skim over these concerns by taking an optimistic view that all will work out for the best without a firm governance framework to steer this. Indeed, these concerns are currently not making the cut when it comes to mainstream scientific and political interest. For example, Defra voiced little concern around how these technologies may simply facilitate a continuation of monocultural farm systems without a clear governance framework to ensure otherwise, in the background documents to the recent public consultation.

If the agroecological community was, therefore, to accept certain forms of genetic engineering, this could help bring nuance to the current polarisation and better progress around these risks may be made. There is a risk that otherwise, the development of a sound regulatory and governance framework that deals with the more systemic risks of this technology will not materialise.

Risks for Agroecology

NGOs have pointed to the failure of GE to tackle systemic issues at the root. The commercialisation of GE could lead companies to promote the use of GMOs instead of more integrated management solutions. These GMOs' risk environmental, social, and economic externalities being maintained. For example, certain livestock diseases, such as porcine reproductive and respiratory syndrome (PRRS) have been linked to high-density pig farms (Velasova et al., 2012). Genetically engineered resistance to PRRS could lead high-density pig farms to be sustained or even intensified. This would have negative impacts, particularly for animal welfare. Similar risks can be claimed for GE disease resistance crops. Companies commercialising these strains might be incentivised to promote them over non-commercial innovations and practices. In short, companies producing genetically engineered organisms might be commercially incentivised to encourage farmers to maintain intensive systems dependent on their gene edited products. This might suppress the development of agroecological solutions that could be more cost-effective and yield a wider range of benefits.

Another concern is that GE will lead to unintended edits occurring in the genomes of GMOs which will have novel and unintended impacts. Evidence has shown unintended genetic material in the genomes of GE hornless cattle (Regalado, 2019). This contradicted the responsible GE company's claims that the cows contained only bovine DNA. The larger risks of this kind of unintended genetic material, are uncertain. However, the case clearly shows the need for thorough regulations, reviews, and testing around the development of GMOs.

Alamy

The unintended spread of GMOs and genetic material into surrounding ecosystems is of great concern, especially to organic farmers. Existing GMOs are rarely farmed near genetically compatible native relatives, this reduces the risk of unintended trait transfer. However, there have been reports of transgene herbicide-tolerant traits spreading from crops to wild species (Zilberman et al., 2018). This threat can be higher for transgenic strains as these varieties could introduce novel genes into ecosystems. Greater understanding of the risk of unintentional spread of genetic material and how to reduce it is important before decisions are made around future GE policies.

Current GMOs have generally been developed for industrialised systems dependent on chemical inputs. Crops such as those resistant to glyphosate can necessitate and therefore lock farmers into chemical input use. These applications of GE can conflict with the aims of agroecology. There is need to explore and develop governance that can reduce the risk of locking farmers into environmentally damaging practices. This stands for conventional breeding as well and GE.

The effects of GE can have completely opposing impacts. For example, genetically engineered blight resistance could reduce the desire to spray crops; glyphosate resistance, however, may encourage continued spraying. This is an example of how the farming system risks associated with GMOs are related to the specific traits that are targeted and the agricultural practices that these traits align with. The hazards relate to the context of use and are not intrinsic to the technology itself.

Based on the evidence, there is potential for GE to benefit agricultural performance, reduce environmental impacts, and potentially support agroecological farming. It is unclear though whether commercial incentives and regulations will enable this to happen. The uncertainty around unintended consequences of GE both upon farmers and upon ecosystems means more research and development of regulations and standards is needed.

2.4 Novel biological controls and inoculants

In the context of this high-level report, a range of microbial and biological techniques have been clustered under the heading 'Novel Biological Controls and Inoculants'.

This encapsulates technologies involving the release of beneficial organisms into an agricultural system to enhance performance. These organisms provide functions such as pest control, growth stimulation and disease reduction. Generally, they remove or reduce the need for chemical inputs, that tend to have higher environmental and social costs.

Biological controls and inoculants are diverse, complex, and context-specific; therefore, it is not practical to undertake an exhaustive review. Instead, several biological control methods have been identified as exemplary technologies. These examples will be used to highlight specific and general opportunities and risks that can yield generic insights about their implementation and governance. Each of the following paragraphs focuses on a different type of biological control.

Microbial inoculation involves the addition of beneficial bacteria to an agricultural system, generally to the soil. Of these bacteria, plant growth-promoting rhizobacteria are among the most effective for supporting crop growth. These bacteria reside in the root systems of plants and exert a positive effect on plant growth. This is achieved

Scenario Analysis of Genome Editing

	Consolidated control	Equitable food system
Agroecological diverse food production	Certain gene edited varieties are approved for use due to proven delivery of public goods. Seed companies, however, control the discourse, advice, and education around the use of seeds. Agriculture is made more sustainable by using more resilient varieties which lower the need for chemical inputs. Yields increase, environmental impact declines but costs rise due to control by seed companies. Influence from seed companies and evidenced information about economic and environmental benefits of their genetically engineered seeds suppress other, less costly practices. Profit margins remain low and pressure to scale remains high as farmers need to offset seed costs.	All new crop varieties, whether produced by gene editing or conventional breeding, go through a systematic review based on the plant's characteristics. Seed reviews are undertaken by a multidisciplinary team that assess the impacts it will have upon agricultural systems. Public awareness around the impact of genetic engineering is high and participation in review and regulation is encouraged. Strains that fail to produce benefits without the use of artificial inputs are restricted. Certain cisgenic crops play a role in helping farmers transition towards more agroecological systems. Impartial advice is available to farmers using all types of seed varieties. All seed varieties are provided with material advising farmers on best agroecological practice.
Intensive agriculture	Deregulation of commercialisation of gene edited highly productive varieties, but only when tied to the use of specific inputs and technologies. Herbicide-resistant gene edited varieties flood the market locking farmers into herbicide use. The economic benefits of these varieties are inaccessible to small scale diverse growers that cannot afford the seeds and technologies. Gene edited varieties make it into the marketplace and do not require labelling. Hence, they compete with conventional varieties and shift the market toward genetically edited, intensively farmed production.	Gene edited varieties increase productivity and lower risk for smaller-scale farms. Resilience increases food security and enables the production of a greater diversity of fruits and vegetables. However, gene editing is tied to chemical inputs and locks farmers into dependence on agricultural inputs. A more equitable but genetically and chemically intensive form of agriculture emerges. Seed producers and agrochemical companies control the advice around farming practice and use of dominant seed varieties.

in a variety of ways. Certain bacterial inoculants enhance the acquisition and availability of nutrients. Others stimulate the production of phytohormones and enhance plant growth regulation. Some bacteria suppress harmful pathogens either by outcompeting them or through enzymatic degradation of cells. Various species also induce greater systemic resistance in crops against abiotic stress. For example, by mediating ethylene response.

Entomopathogenic nematodes are microorganisms that predate upon insects. The genera Heterorhabditis and Steinernema have been developed for commercial pest control. These nematodes go through an infectious life cycle stage in which they enter the body of a host insect and, through a symbiotic relationship with certain bacteria, produce and release toxic compounds. This biological function can and has been exploited for controlling populations of select pest species.

Fungi can provide numerous beneficial services to farmers. Endophytic fungi reside symbiotically within a plant and can benefit crops. They can disrupt the lifecycle of pathogens, induce the plant's defences, or compete with pathogens for nutrients and ecological niches. Entomopathogenic fungi predate upon insects. These species can be used as biological insecticides. They first adhere to the bodies of pest species before penetrating the host's exoskeleton, growing within, and eventually killing the host. Nematophagous fungi are capable of controlling plant-parasitic nematodes. These fungi form a range of traps and adhesive structures that catch pest species.

Sterile insect technique is a method used to manage pests on an area-wide basis. The method requires the rearing and sterilisation, using irradiation, of large numbers of the pest species. These sterile insects are then periodically released into the target area where they compete with wild males to mate with wild females. The females that mate with the sterile males have no offspring leading to suppression of the pest species population (Marec & Vreyson, 2019).

The Current State of the Technology

As awareness of the environmental damage caused by chemical control agents increases, as restrictions to use tighten, and as chemical resistance grows in target organisms; there is increasing demand to find alternative ways to control pests, pathogens, and support healthy crop growth. This has led to growing interest in biological controls, evidenced by rapid annual sectoral growth of 10-25% (Hyde et al., 2019). Additionally, the sector benefits from potential resilience due to a diversity of possible applications. Production methods for biological control may have potential markets within aquaculture and cosmetics as well as agriculture (Askary et al., 2021). Moreover, the sector still has considerable potential for innovation and growth; for example, of the plethora of potentially beneficial species of nematode, only 13 have been commercially exploited (Askary et al., 2021).

Advances and collaborations in multidisciplinary science including microbiology, agro-biotechnology, nanoscience, chemical engineering, and material science will provide an immense opportunity for further development and formulation of advanced biological controls (Dukare et al., 2021). Collaborations and innovations between these fields of research are enhancing the identification, cultivation, enhancement, and deliverance of these beneficial organisms.

Many companies have commercialised biological controls. Biobest sells a range of biological controls for pest and disease control pollination. The products include beneficial nematodes and biofungicides. They also sell a range of products that help farmers monitor insect populations on their farms. This shows how Biobest[6] and biological controls more broadly require a shift in farmer behaviour towards increased observation, reflection, and knowledge building; behaviours also necessary for an agroecological transition. Other established companies in the sector include Koppert[7] and AlphBio Control[8].

There are many examples where the methods described above have been used successfully. Entomopathogenic nematodes have been used to control black vine weevil populations in German tree nurseries. This approach has been so successful that 95% of German tree nurseries have switched to nematodes as their major pest control agent (Askary et al., 2021). Similar success has been reported for the control of pests affecting turf grasses.

Despite the evidence supporting the benefits of biological controls, there are still challenges to scaling the impact of these technologies. The challenges are three-fold, economic, technical, and social. On the economic front, identification, cultivation, and storage of biological control agents are still costly due to a lack of optimisation and standardisation (Dukare et al., 2021). Receiving regulation for the commercialisation of these agents can also be expensive.

Technically there are issues around safety, stability, and consistency. Additionally, many organisms are adapted to specific soil conditions making them less viable across a range of agricultural environments; this can limit the market for products. Another

6 https://www.biobestgroup.com/
7 https://www.koppert.co.uk/pest-control-products/
8 https://alphabiocontrol.com/

CASE STUDY

The yield benefits of Biological Controls

Numerous studies have reported the yield benefits of microbial inoculants.

In wheat, demonstrated yield increases from microbial inoculation have ranged from 13-31% when compared to a non-inoculated control (Santos et al., 2019). These increases can also be enhanced and made more reliable by using multiple microbial strains, a method known as co-inoculation. Co-inoculation of soybean resulted in yield increases of close to 16.1% compared to 8.4% for single strain inoculation (Santos et al., 2019).

Yield increase have also been evidenced when applying beneficial arbuscular mycorrhizal fungi. A large meta-analysis of potato production in 231 field trials in Europe and North America showed that inoculation with a commercial strain of fungi, R. irregularis, resulted in average yield increases of 9.5% of total crop yield. In addition, application of the fungi can enable farmers to reduce fertiliser application without a decline in yield, this can enhance profitability (Chen et al., 2019).

technical challenge is that cultivation before application separates the applied organisms from the original stock by many generations, this can impact product phenotype and function and, therefore, effectiveness (Kaminsky et al., 2019). Variability also makes validating the effectiveness of biological controls in-field difficult (Kaminsky et al., 2019).

Finally, the sector faces social barriers. Market demand for biological controls, although growing, remains low (Dukare et al., 2021). This is largely due to a lack of awareness of these options and a lack of information about their effectiveness (Askary et al., 2021). More broadly, biological controls require a mindset shift. Whilst chemical controls can work without consideration of natural cycles, biological controls generally work best when applied at an opportune moment, either in the lifecycle of the crop or pest. This requires a form of observation and reflection that may be unfamiliar to many farmers. Farmers using biological controls will have to rely on a suite of options to enhance the resilience and performance of plants and suppress antagonistic organisms. This requires a different set of skills than is currently applied to conventional systems.

Opportunities for Agroecology

Biological controls have considerable potential for helping farmers shift from conventional to agroecological farming. Most of these products can be applied using conventional farming equipment and can therefore replace chemical inputs on farms. Optimal use requires an agroecological approach that fosters healthy ecosystem functioning and, hence, minimal chemical application. However, these biological controls can still function alongside conventional chemical inputs. Therefore, they can provide a potential gateway for farmers seeking to transition to an agroecological approach.

Unlike chemical agents, biological controls often rely on good ecological health to function effectively. Beneficial nematodes, fungi, and bacteria all function better if they have good quality soil to inhabit. In turn, many of these additives provide ancillary functions that improve soil health (Askary et al., 2021). Many of these biological controls are specific to target pests, this minimises the risk of unintended consequences and enables healthy ecosystem functionality to be retained (Askary et al., 2021).

Askary et al. (2021) propose that biological controls are suitable for a decentralised, regionally specific form of production. They recommend local small-batch custom production. Biological controls cultivated for a specific region can be more viable due to greater adaption to environmental conditions and local pests. Local production can also reduce transport, packaging, formulation, and storage costs. Moreover, this kind of local production aligns with the localisation of supply chains, seed networks, and knowledge production. Localised biological control production could also give farmers more influence over and insight into the types of products that are produced for their systems, helping to enhance farmer autonomy.

Risks for Agroecology

The fate of the organisms added as biological controls are still uncertain. Studies have found that applied microbial inoculants can persist for decades after first inoculation (Kaminsky et al., 2019). This is not to say that persistence is inherently problematic, but there is certainly a need for continued investigation into the fate of these products. There is also uncertainty around the spread of these products. Ideal inoculants should not spread far from the site of application; will persist only through target functional periods; and will not have negative impacts on human or environmental health (Kaminsky et al., 2019). Spread and persistence are both important features for further study, particularly as interest in these products grows.

Biological controls are currently a high-cost niche product. This makes them inaccessible to many farmers. Moreover, many products are specific to singular crops and species. It is likely, at least in the short term, that these products are only accessible to larger-scale farmers. Smaller and highly diverse farms may not have the finance or economies of scale necessary to offset the cost of these products. Whilst this is likely to change in time as production is scaled and optimised, producers must consider the needs of highly heterogeneous systems.

Scenario Analysis of Novel Biological Controls and Inoculants

	Consolidated control	Equitable food system
Agroecological diverse food production	Biological controls remain high cost and the technology for production is only accessible to large conglomerates that control the market and pricing. This means only large scale highly productive farms can afford biological controls. This leads to a new form of large-scale organic that is highly profitable with low environmental impact but outcompetes many smaller and less productive farms.	Biological controls have largely replaced artificial inputs in agroecological systems. Optimisation, standardisation, and governmental support has helped reduce costs making biological controls an economically viable option for most farmers. Farmers have access to a wide variety of biological controls and advice on how to utilise them, both from peers and impartial consultants. A form of agriculture dominates in which farmers are taught and encouraged to observe and respond to the natural cycles of their systems. Biological controls are produced locally by decentralised organisations that cultivate varieties specific to local agroecosystems. Farmers are involved in production and testing.
Intensive agriculture	Large agrochemical companies invest in biological controls buying up start-ups and drowning out the competition. These companies promote biological controls as an additive to conventional production and not as a gateway to more agroecological production. Biological controls are sold alongside chemical inputs. This consolidated control of the sector restricts a transition to agroecological production.	Biological controls are made accessible but only through economies of scale, standardisation, and promotion. This creates an environment that encourages farmers to depend on biological control products and neglect more integrated agroecological approaches. Farmers use biological controls in the same way as chemical inputs are used in conventional systems. There is little focus on observations, monitoring, awareness, and education. Products are therefore used inefficiently and unsustainably.

3. Technologies for Impact monitoring

3.1 Remote Sensing of Environmental Impact

Improving the sustainability of land management at any scale requires an understanding of the condition of that land and how that condition is changing due to any intervention.

This understanding requires the gathering of information related to specific indicators. These indicators, when selected well, accurately reflect the state of something that is being measured. For example, the number of nests can be used as an indicator for the abundance of a certain bird species. Selecting, gathering, and processing this information can be arduous and costly.

'Remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft). Special cameras collect remotely sensed images, which help researchers "sense" things about the Earth.'[9]

Remote sensing offers a way to gather information on indicators of environmental condition in a less intrusive, less costly, and more efficient manner. It can also provide information across larger and less accessible areas. Moreover, this information can be provided regularly with technologies now capable of imaging the earth's entire surface daily[10].

As more actors seek to improve their environmental impact, accurate and continuous information streams become increasingly important. Governments seek to enforce policies and regulations in more efficient ways and need to track progress towards net-zero targets. Green investment funds wish to validate their impacts. Carbon brokers need to guarantee permanence and farmers want to better understand their land and prove adherence to agri-environmental schemes.

Remote sensing, particularly when combined with machine learning, has the potential to track and interpret a huge amount of data in real-time. High resolution and thermal imaging of habitats, species abundance, deforestation, forest fires, poaching, and fishing will transform our capacity to track global biodiversity and respond rapidly to changes. Multispectral and hyperspectral cameras have the potential to enable accurate tracking of GHG emissions, and carbon sequestration across the globe. Soil spectroscopy in particular holds great potential for in-field validation of soil carbon sequestration, which would help unlock agricultural carbon markets. A particularly noteworthy project is the DeepC System, which has just been awarded $3.25 million by the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E).[11] Continuous imaging will enable the identification of land management changes from ploughing to cover cropping as they happen.

Remote sensing data could have huge benefits for environmental markets. It will enable purchasers and providers of environmental services to efficiently validate the provision of the agreed services. Breaches of agreements will also be identifiable making the investments more reliable.

9 https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used?qt-news_science_products=0#
10 https://www.planet.com/products/planet-imagery/
11 https://www.agriculture.com/news/technology/soil-health-institute-to-develop-soil-carbon-measurement-and-monitoring-system

The Current State of the Technology

Remote sensing by satellite imaging has undergone considerable growth and transformation in recent years. Technological advances, including reduced camera size, have enabled numerous public and, more recently, private projects to take place.

The Copernicus programme is a particularly important example. Since the first launch in 2014, the programme has sent up a fleet of satellites that gather and make publicly available super spectral imagery. By 2030 the programme aims to send 20 more satellites into orbit dramatically increasing the programme's capacity for data collection. There are also several hyperspectral satellites currently in orbit such as EnMAP, HyspIRI, and PRISMA (Angelopoulou, et al., 2019).

Planet Labs is a private company founded in 2010 that now maintains an orbiting fleet of more than 120 inexpensive and compact satellites. The company aims to increase information gathering to help with life on Earth.

Remote sensing is not limited to satellites, unmanned aerial systems (UASs), or drones, offer a viable alternative to conventional platforms for acquiring high-resolution remote sensing data. They can achieve this at a lower cost, with greater flexibility and versatility (Klemas, 2015). Hardin et al. (2018) write how UAS developments since 2011 have helped overcome many of the challenges that restricted their use in environmental monitoring. UASs are now capable of carrying an array of remote sensing technologies including multispectral, hyperspectral, lidar and thermal sensors.

Opportunities for Agroecology

The remote sensing of environmental impact has considerable potential to support a transition toward agroecology. Automated measurement of soil carbon could enable soil carbon payments for farmers, thereby rewarding agroecological practices. Likewise, more accurate observation of biodiversity could incentivise investment in farming that proves to be less detrimental to species abundance. This is likely to support agroecological systems such as those implementing extensive grazing.

Tracking soil water profiles would reveal the forms of agriculture best suited to flood risk reduction. It would likely highlight agroecological practices like permanent ground cover, agroforestry, and no-till systems as important for protecting flood-prone areas. This could encourage agroecological investment by municipalities, water, and insurance companies. Remote sensing may also lower the cost of achieving certifications. This would benefit smaller producers who may not have had the capital to pay for more costly certifications.

Risks for Agroecology

If remote sensing is only accessible to specialists and requires contracted professionals to interpret the data, it is likely to be prohibitively expensive for less profitable/small scale farms.

Another risk is that algorithms may not be designed to deal with the complexity of agroecological systems. This could disadvantage agroecological farms, as they would not receive automated validation in markets and schemes. Monitoring could be more arduous and costly for these systems which would disincentivise system complexity.

It is also important that the risk of unequal and exploitative data control and ownership is avoided. As private organisations enter the sector there is a risk that data becomes commodified and exploited to drive private interests. It is not unfeasible that an agricultural technology company would want to pay a satellite company for information enabling them to target certain farmers with adverts tailored to their needs. This brings into question issues around ownership and commodification of imagery.

3.2 Big data analysis and environmental footprint accounting

The collection, storage, and analysis of big data in agriculture, supported by a rise in the use of sensors on farms, has considerable potential for transforming the agricultural sector.

Although the applications of big data analysis are varied, here, to avoid overlap with other sections, we focus on the potential of data technologies to unlock greater traceability and transparency in the food system.

Big data can be described as the collection of data that cannot be captured, curated, managed, and processed with traditional methods or tools within a useful time frame. Big data has been characterised according to five dimensions, volume, velocity, variety, veracity, and valorisation. These dimensions make effectively searching, visualising, and cross-referencing big data in real-time a key challenge. If the challenge is overcome, insights and information can be extracted that would otherwise be unfeasible. These insights can enhance understanding and decision making at a variety of scales.

Big data analysis in the agricultural sector is particularly challenging given the complex, diverse and unpredictable data that is collected (Kamilaris et al., 2017). The technologies that are most utilised to aid data analysis are machine learning, modelling and simulation, statistical analysis, and normalised difference vegetation indices (NDVIs) (Kamilaris et al., 2017). These tools help store, share, process, classify, cluster, analyse, and visualise the huge amounts of diverse data that can be collected on farms.

Big data analysis technologies can increase the usability of remote sensing data. A plethora of software packages has been developed to aid the processing of the large data sets gathered by remote sensing. These programmes save huge amounts of time by removing the need for manual georeferencing, a process that translates images into uniform map-like geometric data files suited to analysis (Hardin et al., 2018).

Advances in big data processing are revolutionising the way remote sensing data is processed. The scale and speed of image processing are being enhanced by cloud computing, machine learning, and advances in high-performance computing (Wang et al., 2018). This is enabling insights and responses to remote sensing to be realised almost in real-time. Advanced data processing also enables multiple remote sensing datasets to be analysed, compensating for the limitations of single sensors, improving accuracy.

Weersink and Fraser (2018) give three areas of agriculture where big data analysis is especially beneficial. Bioinformatics involves the use of computation to analyse biological data. Advances in this area are accelerating

Scenario Analysis of Remote Sensing of Environmental Impact

	Consolidated control	Equitable food system
Agroecological diverse food production	Improved data collected through remote sensing enables certain farmers to validate their environmental impacts and access environmental markets. However, data is not public or open source. Hence, advice and access remain restricted and costly. Little effort has been exerted to increase the usability of the data collected. This means only the most productive and specialised farms can afford to utilise the remote sensor data collected.	Remote sensing technology and data to assess numerous agri-environmental indicators are accessible to all farmers. Farmers can use remote sensing to measure indicators such as soil carbon content and biodiversity in real-time. This enables them to better access environmental markets. Remote sensing technologies are integrated into agri-environmental schemes, environmental markets, and certifications to lower the cost of monitoring and validation. Sensors are modular and work with a variety of technologies and systems. Data collected on farms is made accessible to farmers and can be shared freely with third parties. Researchers are encouraged and enabled to use the public data to enhance understanding of how integrated systemic changes impacts a variety of indicators. This research is used to enhance collective understanding of how to optimise agroecological practices.
Intensive agriculture	Remote sensing data is privatised and made inaccessible to most actors. Few parties other than major agricultural technology and chemical companies can exploit the data. They use this data to promote advice encouraging the purchase of their products, which are largely aligned with an intensive approach to agriculture.	Remote sensing data is made open source, but little effort is exerted to monitor complex environmental indicators and how they interact to enhance performance. Hence, data collected is used for enhancing productivity and system simplification, which is more convenient to analyse using remote sensing. This incentivises sustainable intensification but falls short of stimulating agroecological transition, which is more complex to assess with remote sensing. There is some effort to create soil carbon sensing and markets. However, poor compatibility with complex systems leads land to be shifted to carbon sequestration rather than food production. The approach fails to create an integrated approach to carbon sequestration on farms.

and reducing the costs of breeding crops and animals. We consider the risks and opportunities of this application to be broadly similar to those covered in Section 2.3. Precision agriculture uses big data to calculate more efficient application of inputs. This we term Smart Agriculture and cover in Section 2.1. Finally, big data analysis across the food chain can enhance transparency and traceability. It is this final application of big data that will be given the most attention in this section.

Big data analysis has the potential to reduce the cost of tracking environmental performance for numerous attributes across the supply chain. This can increase reliability and lower the cost of environmental certification. It can also support verification of environmental compliance and identify non-compliant actors. Additionally, this traceability can unlock environmental markets and financial mechanisms supporting good environmental practice. Finally, it can enhance consumer awareness and guide ethical consumption.

Tracking of environmental performance is needed if farms, companies, and governments want to prove they are responding to mounting pressure to decarbonise. Hence, there is a need to record the environmental footprint of products from cradle to grave. This is a complex and potentially costly undertaking, evidenced by Tesco's decision in 2012 to scrap a promise made in 2007 to provide carbon footprint labelling on all their products[12].

Big data analysis, blockchain, and other digital technologies such as quick response (QR) codes, radio-frequency identification (RFID), near field communication (NFC), online certification and digital signatures, sensors and actuators, and mobile phones, can provide an efficient and reliable way of tracking environmental impacts (Kamilaris et al., 2019). The efficiency benefits of these technologies were evidenced by a study that showed traditional tracking of mangoes from supermarket to farm took 6.5 days but with blockchain took just a few seconds.

Using these technologies in conjunction with remote sensors, actors along a supply chain could efficiently and anonymously share details about origin and production, including pesticide, fertiliser, and fuel use. Accurate information could therefore be made accessible to consumers and regulators. This could enable environmental accounting and support efforts to invest in ecological restoration and implement pollution and carbon taxes. Such a system, proposed and designed by Shakhbulatov et al. (2019), demonstrates how digital technologies such as blockchain can reduce the complexity and maintain privacy when tracking the carbon footprint across the food supply chain.

The Current State of the Technology

Several businesses have developed technological infrastructures that facilitate big data applications in farming. John Deere has developed FarmSight[13], a data platform that enables them to enhance the service they provide to farmers, sharing advice in real-time, and proactively replacing parts. Monsanto has developed FieldScripts, which supports precision farming but is tied

to Monsanto seeds and products. These are examples of closed networks where businesses are using big data to enhance their commercial offerings. Farmobile[14], on the other hand, provides a piece of hardware that can be integrated with various machinery to capture and share data.

In Europe, an open-source platform has been developed called FIspace[15]. The aim is to enhance business to business collaboration, data sharing, and increase access to big data analysis for small- and medium-sized companies.

There are many examples of blockchains use in the food supply chain. These mostly relate to improving traceability. WWF has used blockchain to tackle illegal tuna fishing, enabling the fisherman to register their catches on the blockchain through RFID e-tagging and scanning fish[16]. The Grass Roots Farmers' Cooperative[17] uses blockchain to communicate information on animal provenance and welfare to consumers. The Sustainable Shrimp Partnership (SSP)[18] has collaborated with IBM to use its Food Trust ecosystem to provide complete traceability of SSP shrimp for their consumers.

There is still considerable mistrust of data companies and many actors are unwilling to share data with third parties; in certain cases, this may be justified, but in others, it is likely to slow the pace of development and restrict the insights that can be yielded. There is a need for consistent policies on data ownership, copyright protection, and data security (Kamilaris et al., 2017). Communicating these policies effectively to farmers and increasing transparency is likely to increase farmer involvement in data networks.

There is a need for greater investment in cloud infrastructure to support the storage, analysis, and visualisation of agricultural data. This infrastructure should be made inexpensive and accessible to non-technical users. Moreover, the use of common technologies and ontologies could enhance open-source data analysis and increase interoperability and data integration (Kamilaris et al., 2017). Coupling this with an increase in publicly available big data sets could greatly improve access to big data analysis and its benefits. GODAN is a particularly noteworthy example of a platform that is working to enhance food security by providing open access to data[19].

Opportunities for Agroecology

Accurate environmental impact tracing, tracking, and labelling could stimulate market demand for sustainable, local agroecological produce. Likewise, forcing companies to communicate the environmental footprint of their products could encourage them to purchase from less damaging sources.

If accurate environmental accounts were kept it could enable externalities such as runoff, pesticide risk, and greenhouse gas (GHG) emissions to be taxed. This could encourage producers and actors across the supply chain to shift to agroecological production methods to avoid increased costs.

Increased traceability of meat and transparency in the meat industry could drive certain consumers away from intensively farmed products, encouraging the purchase of extensively grazed agroecological meat.

12 https://www.wired.co.uk/article/carbon-labelling-quorn
13 https://www.deere.co.uk/en/parts-and-service/services/farmsight/
14 https://www.farmobile.com/
15 https://www.fispace.eu/index.html
16 https://www.wwf.org.nz/what_we_do/marine/blockchain_tuna_project/
17 https://grassrootscoop.com/pages/our-farms
18 https://www.sustainableshrimppartnership.org/
19 https://www.godan.info/

At the FABulous Farmers non-chemical weeding day researchers demonstrate a thermal imaging device which helps farmers identify weeds in their fields

FABulous Farmers

The benefits of labelling are likely to be greater for producers who have direct relationships with consumers as they will be more capable of receiving higher prices for ethically labelled goods (Weersink & Fraser, 2018). In this way, environmental traceability may incentivise more localised supply chains and greater connectivity between farmers and consumers.

Risks for Agroecology

There are risks associated with environmental footprint labelling. If only select impacts are communicated there is a risk that other impacts, and particularly those difficult to quantify, could be ignored. This may have unintended side effects. For example, consumers might be encouraged to buy low carbon footprint chicken, that has dismal welfare standards. On the other hand, communicating large amounts of environmental information could confuse consumers, leading them to simply ignore the information for clearer indicators such as price and nutrition.

Issues around big data more broadly include the creation of monopolies and farmer dependence on large corporations, privacy issues, and unequal access. Worries about increased corporate control over data flows have been fuelled by multiple acquisitions of data technology companies by major businesses in the agricultural sector, including Monsanto and John Deere. This has led to fears that these companies would use this information to promote their products and identify opportunities for further market control (Weersink & Fraser, 2018).

There is also the risk that if big data analysis requires specialist knowledge and high levels of investment, then it and the role it can play in enhancing precision agriculture, informing decision making, and validating impact may be inaccessible to smaller farms. This would disproportionately advantage larger farms and may increase land consolidation and farm scale.

Scenario Analysis of Big Data Analysis and Environmental Footprint Accounting

	Consolidated control	Equitable food system
Agroecological diverse food production	Big data analysis through private data platforms allows more precise approaches to be applied lowering resource use. Precision strip agriculture, IPM, and biological controls are enhanced by and integrated into this big data approach. However, access to these data platforms is tied to the use of specific products and technologies. This creates lock-ins and market controls by the technology companies. Moreover, this data approach is only accessible to farmers that can afford the technology. This, therefore, creates a landscape where highly efficient and sustainable data-rich farms have a considerable advantage over other farms. Further consolidation of land ownership becomes a risk.	Farmers have open access to user-friendly data storage, analysis, and secure sharing platforms and data visualisation tools. Platforms are interoperable and work with most technologies. Flexibility accommodates new technologies such as enhanced soil testing and remote sensing. Actors across the supply chain can use these platforms to validate the environmental impacts of their products. The platform is used to unlock environmental markets, carbon taxes and offsetting, environmental footprint accounting, and sustainable food procurement. Data sharing on the platform facilitates more efficient validation of compliance with agri-environmental and more efficient certification.
Intensive agriculture	Private big data analysis platforms created by large agricultural technology companies dominate the sector. The analysis of data and insights are tied to the use of products produced by these companies, locking farmers into the use of specific and conventional technologies. Control of the data facilitates greater market control by these companies, they control the discourse and advice provided to farmers who become locked into a conventional approach.	Data platforms are made open-source and accessible. However, there is little attention paid to environmental tracking and tracing. Instead, data analysis applications support more intensive precision agricultural approaches that are tied to the use of conventional agricultural inputs and practices.

4. Supply Chain Technologies

4.1 Digital Food Hubs & Dynamic Food Procurement

ICT is enabling the development of digital food hubs and dynamic food procurement systems. The expansion of the internet and the increased computational ability of people may facilitate the development of localised, efficient markets across the country.

Digital food hubs can act as an intermediary organisation that facilitates the aggregation and distribution of source-identified products from local and regional producers to wholesale buyers and directly to consumers (Berti & Mulligan, 2016). Digital food hubs facilitate strategic alliances which help multiple participants achieve a shared goal, this normally being improved access to markets by acquiring some of the economic and logistical efficiencies of conventional food supply chains.

Food hubs have the potential to improve the viability of small and medium-scale farms and more equally distribute the power and economic value among all actors involved (Berti & Mulligan, 2016). These hubs are usually more transparent; they can provide an important role in supporting community understanding of agriculture, strengthen relationships between farmers and consumers, support higher levels of local employment, stimulate local socio-economic vibrancy and health, and support more diverse growers, which are often more environmentally sustainable (Berti & Mulligan, 2016).

Traditionally the challenge has been in how to scale up these food hubs without losing their social environmental and positive localised economic impact (Berti & Mulligan, 2016). Also, the economic, organisational, and physical structures are often missing to facilitate local food supply chains. Moreover, the sustainability of localised food hubs is not guaranteed, and local should not always be assumed to be better as is sometimes the case. Additionally, some critique food hubs, claiming they are elitist, exclusive, and inequitable. Proving more of a romanticised ideal about localisation than a viable food supply chain. Testament to this is the financial frailty of many of these organisations and the minor role they play in national food markets.

Dynamic food procurement is one method to alleviate some of the issues associated with food hubs. Dynamic food procurement systems enable large food procurers, such as public sector institutions, to source their supply from multiple smaller scale, sustainable, local growers. The ability to supply to these larger procurers can provide greater financial security to actors across the supply chain enabling the technical, logistical, and social aspects of the system to become established. At the same time, technology can now facilitate supply flexibility, balancing the needs of the producer with the needs of the procurers. This avoids asserting pressure onto producers to scale at the cost of sustainability.

It is hoped that dynamic food procurement can enable greater transparency across food supply chains enabling public sector institutions to validate their environmental impact. This will be incentivised by governments needing to prove their progress toward net-zero. In turn, public sector support

might act as a catalyst for establishing more localised, sustainable, and transparent food supply chains. These supply chains may become more attractive to forward-thinking private businesses and may eventually facilitate the implementation of policies that enforce environmental accounting, labelling, subsidies, and taxes across the food supply chain.

The Current State of the Technology

There are many established digital food hubs. The Open Food Network is a software platform that allows farmers to sell food as an individual or as part of a community. The open-source software enables farmers to customise their online enterprise, add products and plan deliveries[20]. This service provides flexibility to the farmer and the customer who can choose between pre-selected veg boxes or specific options.

Farmdrop claim to provide high quality sustainably produced home grocery deliveries[21]. This service operates more like a conventional store, giving users flexibility in their purchasing. It also sells a variety of processed and branded goods. The increased usability and flexibility appear to be reflected in a higher price bracket. Numerous farms and localities also provide veg box deliveries, such as Purton Organics[22]. These boxes are more cost-effective but give consumers less flexibility in their purchasing.

Equilibrium Markets is a cloud-based technology platform that facilitates dynamic food procurement, fulfilment, consolidation, and delivery of food for the public sector[23]. The agility of the platform provides flexibility to the procurer, the producer, the supplier, the chef, and the diner. This agility is suited to shorter, transparent, and efficient supply chains. Transparency is key to the platform and environmental impact data is communicated directly to the procurer enabling them to select products with a smaller footprint and validate the impact of their purchasing. This enables procurers to shift their purchasing towards lower environmental impact. If dynamic food procurement were applied to the whole £2.6 billion public sector food supply, it could have substantial environmental and social impacts.

Opportunities for Agroecology

Dynamic local supply chains benefit from diversity. If food hubs and dynamic food procurers can source a greater range of produce locally these supply chains are made more viable. In this way, local supply chains encourage system heterogeneity, a core agroecological principle.

Greater transparency will enable producers, procurers, and consumers to better understand and communicate the environmental impact of food. This could act as a catalyst for more environmentally sustainable consumption, driving consumers towards agroecological food production.

An additional benefit of these systems is that they do not necessitate increasing scale. Whilst scale is not inherently bad, economic pressure to scale to meet market demand at the cost of environmental sustainability is. Scale agnosticism in supply chains can be achieved through increased flexibility and should be prioritised to better support an agroecological transition.

Risks for Agroecology

There is a risk that consumers assume food supply is sustainable simply because it is local. This could lead consumers to blindly support farmers

Fresh-range

20 https://openfoodnetwork.org.uk/
21 https://www.farmdrop.com/shop
22 https://www.purtonhouseorganics.co.uk/
23 https://equilibrium-markets.com/index.html

Scenario Analysis of Digital Food Hubs & Dynamic Food Procurement

	Consolidated control	Equitable food system
Agroecological diverse food production	Private digital food hubs become established and dominate the sector. They supply local, sustainable produce and communicate information about various environmental impact indicators. However, the products are sold at a premium. These local markets are financially inaccessible to most consumers and remain niche. This in turn means only a limited number of farmers can benefit from these supply chains.	Open-source flexible digital food hubs and dynamic food procurement give farmers access to local markets at fair prices. Transparent labelling and communication allow farmers to share information about their impacts and for consumers to easily access this information. Public sector procurement is sourced from local agroecological producers. Environmental impact indicators of public sector procurement are measured, recorded, and communicated across the supply chain. Other actors are encouraged to follow this example. Funding opportunities are available for the enhancement and consolidation of local, sustainable, and transparent food supply chains.
Intensive agriculture	Private digital food hubs establish selling local food at a premium. They communicate no meaningful information about the sustainability of the products but optimise local supply chains and profit off their role as aggregators and use data collected to expand their markets and enhance their brand.	Digital food hubs and dynamic procurement is established but environmental impact indicators are neglected. This leads to limited consumer and procurer understanding of product sustainability. Hence, local, and equitable supply chains are developed but they do little to transition farms and consumers towards agroecological production.

that are implementing poor practice simply because of their proximity. The sustainability of localised food supply chains is not guaranteed, and local should not be assumed to be better as is sometimes the case.

4.2 Smart Technology for Food Consumption

Household food waste in the UK contributes 6% of the nation's carbon footprint (Chapagain and James, 2011). In the EU household food waste accounts for half of all wasted food.

Reducing this wastage would have a substantial impact on the emissions of the food sector, and the demand for food. This could, in turn, influence the pressure for increasing agricultural productivity.

Wasting food is a highly complex behaviour deeply entangled in cultural and social norms and routinised behaviours. However, technology may offer potential solutions. Hebrok & Boks (2017) describe three categories of food waste reducing technologies, smart fridges, and apps to track food, packaging to improve shelf-life, and various items to nudge consumers into wasting less.

Broadly speaking, these technologies attempt to create a postharvest supply chain where the consumer is made more aware of their food consumption behaviours. It is possible to paint a picture of what this future food supply chain may look like. Whilst in the shop, apps synchronised with sensors in the

consumer's fridge will inform them what items they need to buy, reducing the risk of overbuying.

Smart technology in the supermarket could automatically set prices to stimulate demand for surplus produce and reduce the price of food nearing its sell-by date. Purchased produce will automatically upload onto the consumer's app which will plan options for cooking throughout the week, prioritising the use of foods with shorter shelf lives. It may also advise the user about optimal storage, which will be extended by smart intelligently designed divisible packaging. This packaging might include tags that are automatically scanned by sensors in the consumer's fridge, cupboards, and bins.

The information gathered by this smart technology will be communicated to the user and calculate how future consumption can be optimised to reduce food waste, maximise nutrition, reduce cost, and enhance sustainability.

The Current State of the Technology

Given the amount of food wasted, numerous companies have been established to combat the problem. These companies can be grouped into four categories.

First, are those companies developing solutions for smart supply and purchasing of food products. Wasteless provide digital pricing labels that mediate the price according to how close a product is to its sell-by date. The system alerts the store when items are nearly out of stock or have been on the shelf for a long time. Wasteless expects that their system can halve food waste and boost revenues[24].

24 https://www.wasteless.com/

Winnow is a solution for restaurants and caterers that uses cameras and scales to track food waste as it is thrown away. This provides insights to commercial kitchens about what is being wasted and how they can reduce this wastage. According to Winnow this can reduce food waste by over half and cut food costs by 2-8%[25].

Full harvest, Hungry Harvest and Imperfect Foods all provide platforms or deliveries that facilitate the sale of imperfect produce that may have otherwise gone to waste[26,27,28].

The second category of companies includes those selling innovative packaging solutions to reduce food waste. Research has shown that packaging issues may lead to 25% of household food waste (Hebrok & Boks, 2017). These issues include packages that are difficult to empty and confusing date labelling (Hebrok & Boks, 2017). Innovations such as multilayer barrier packaging, modified atmosphere packaging, edible coatings, and moisture absorbers can all prolong shelf lives.

Multiple companies are innovating in this sector. Apeel[29] is a company providing plant-based protection for fruit and vegetables. Their coating ensures produce lasts at least twice as long as untreated produce. Hazel Technologies[30] supply small sachets that can be thrown into packaged fresh produce to increase preservation. The packages work by reducing respiration rate and increasing resistance to ethylene. Bluapple[31] provides a range of bags, mats, and filters to increase the longevity of produce in the home.

Innovative date labelling technology on the packaging is also being used to lower food waste. These include bioreactive food expiry labels that are smooth when the food is fresh and lumpy when it is expired. An example being those produced by Mimica[32]. Similarly, the keep-it label[33] continuously monitors temperature and time and visualises the time left to expiration through a decreasing line.

The third category relates to companies innovating smart storage and consumption. Several smart fridge designs have been proposed and developed for reducing food waste. These include app integration and communication, colour coding to improve organisation and raise awareness, and fridge cams. Fridge cams are a range of cameras on the market that photograph the insides of fridges to inform users about what they need whilst away from home. Some of these cameras also integrate with home delivery apps to automatically update shopping baskets.

The final category covers companies providing innovative solutions for food sharing. The aim is to reduce food waste by enabling consumers and restaurants to distribute food that would otherwise be wasted, to those wanting it.

Food Cloud[34] is an Irish charity that uses IT solutions to connect sources of food waste such as farms, manufacturers, and supermarkets with charities that can distribute the produce to those in need. Olio35 is a mobile app that reduces food waste by enabling food sharing. The platform has over 2.5 million users and

25 https://www.winnowsolutions.com/
26 https://www.fullharvest.com/
27 https://hungryharvest.net/
28 https://www.imperfectfoods.com/
29 https://www.apeel.com/
30 https://www.hazeltechnologies.com/
31 https://thebluapple.com/
32 https://www.mimicalab.com/
33 https://keep-it.com/
34 https://food.cloud/
35 https://olioex.com/

claims to have facilitated sharing of nearly 10 million portions of food.

A critique of food sharing innovations is that they do not tackle the systemic issue of food waste. They can allow the actors most responsible for the waste to perpetuate poor practice whilst shifting responsibility for wasted food onto other actors such as charities.

There are also several noteworthy European campaigns aiming to raise awareness and change behaviours around food waste. These include Love Food Hate Waste in the UK, Matvett in Norway, Klieklipedia in the Netherlands and Stop Spild af Mad in Denmark. These campaigns provide information to consumers about how to use leftovers and correctly store food. There is a risk, however, that these resources only appeal to consumers who are already aware of and reducing their food waste (Hebrok & Boks, 2017).

Opportunities for Agroecology

Less waste may lower the demand for food. This would reduce the pressure on land for intensive production meaning lower-yielding and more extensive systems may be more viable. Additionally, waste reduction can be equated to financial savings for consumers, and procurers. Consumers may therefore be more willing to spend on better quality agroecological products.

It has been shown that consumers who are encouraged to undertake sustainable behaviours in one area of their lives are more likely to begin viewing themselves as environmentally conscious individuals. This may stimulate more environmentally positive consumption. This is something that should be consciously nurtured through collaboration between developers of waste reduction apps and other actors in the agroecological food supply chain.

This, however, is not intrinsically true and consumers are just as likely to maintain conventional buying habits with reduced waste. Apps could be paired with advice about sustainability, transparency, and seasonality; thereby, increasing awareness about the benefits of agroecological production.

Risks for Agroecology

Several potential risks have been hypothesised by the author; firstly, it is likely that advances in equipment and materials to package for longer shelf life are less accessible to small scale diverse growers. This could lead to comparatively higher food waste in shorter supply chains. However, this might also be counterbalanced by the increased freshness of local produce. A similar issue relates to high tech smart apps and fridges. These systems may not work with locally sourced produce and could disincentivise consumers to purchase directly from farms.

A final comment is that consumers often misjudge the scale of different environmental risks. In an extensive review of academic literature on food waste, Hebrok & Boks (2017) state that it is generally agreed that the benefits of packaging for increased longevity outweigh the benefits of reduced packaging and biodegradability. This is not the public consensus though with high profile campaigns driving down the use of packaging. Packaging reduction is important, but the benefits of its use need to be understood and communicated to ensure consumers support the most environmentally positive options.

Scenario Analysis for Smart Technology for Food Consumption

	Consolidated control	Equitable food system
Agroecological diverse food production	Food waste-reducing technology works with a diversity of products. However, cost means that only large-scale producers selling through conventional supply chains can access the technologies. This means a proportion of small to medium scale producers are excluded from the use of these technologies. Whilst the benefits of the technology incentivise more producers and consumers to sell to and buy from supermarkets. This consolidates control of the food sector.	Packaging and storage technologies are accessible to actors across all supply chains. Policies and incentive schemes are structured to support the use of longevity enhancing products. Collaboration and interoperability are encouraged between the diversity of companies working to reduce food waste. Companies working to reduce food waste also work to inform consumers of agroecological production and its benefits. Awareness about food waste and being reflective about consumption is taught throughout education. Awareness and education about food waste are built into the supply chain. Package and storage designers are encouraged to think about alternative supply chains as well as supermarkets. Efforts to reduce food waste are focused on the point of sale. Interventions here have a significant impact with fewer actors involved. Building developers are incentivised to install intelligent food waste reducing technologies. Large scale accommodations such as those in universities are incentivised to integrate food waste saving technologies into their buildings to promote best practice.
Intensive agriculture	Food waste-reducing technologies are only accessible to large scale standardised producers. This means small to medium scale highly diverse farmers are disadvantaged. Consumers are incentivised to purchase less agroecological aligned produce due to convenience and product longevity.	Solutions are modular, affordable, and hence accessible to most producers. However, the products are designed for standardised systems and singular products. This means farmers producing highly diverse foods cannot benefit from the products. Lack of flexibility in design and limited designer awareness of agroecological requirements mean these products support intensive agricultural practice.

5. Technology Influencing Agricultural Demand

5.1 Cellular Agriculture

Cellular agriculture refers to the production of agricultural products from cell cultures. This usually involves the production of animal products, such as meat, fish, and dairy.

The aim is to meet the demands for these products without the associated environmental, ethical, and human impacts of livestock production.

Cellular agriculture can be split into two types. Tissue engineering produces cellular meat engineered from cell or cell lines taken from living animals. The technology involves expanding and differentiating stem cells to produce muscle cells. Chemical, biological, or mechanical stimulation in the cell culture media is used to mediate this growth. Scaffolds can also provide a way to guide tissue growth. The second type of cellular agriculture is fermentation-based. This method does not use any tissue from living animals but instead typically relies on genetically modified bacteria, algae, or yeasts that produce the desired organic molecules.

A major driver of cellular agriculture is the desire to lower the environmental impacts from livestock production. Tuomisto et al (2011) found that cultured meat produced 78-96% less greenhouse gas emissions, 82–96% less water use, and 7–45% less energy use than conventional meats. It can also lower demand for land and issues such as eutrophication, antibiotic use, and disease. There is also less waste due to unwanted parts of a carcass. However, other research has shown that the energy use of cultured meat may be higher than for certain kinds of conventional meat and for many more common meat alternatives (Mattick et al., 2015; Smetana et al., 2015).

The technology could also impact supply chains. If technical and consumer perception issues can be overcome there is potential for these technologies to stimulate structural change in food systems. As it is unrestricted by the land quality and area it has been proposed that cultured meat could enable more of the global population to access protein.

This technology could also have cultural impacts. Job availability in abattoirs, and across the meat supply chain could shrink. On the other hand, a new sector of work may materialise within the cellular meat sector. Engineers, biotechnologists, food technologists, and nutritionists will be required to enhance the process of cellular agriculture. Whilst it is difficult to say how the aggregate level of employment would be affected there would be a shift towards jobs requiring higher levels of education. This would have political and social ramifications.

Despite the high amount of attention cultured meat is receiving there are questions around the plausible scale of its impact. Large scale production at a competitive enough price to affect global greenhouse gas emissions is challenging. Stephens et al. (2018) predict that, if it is even possible, it will take decades to scale the cultured-meat sector to a point where it will have a significant impact. Whilst initial breakthroughs have stimulated high investment in the sector, the challenges of scaling may suppress this financial flow.

On the other hand, cellular agricultural production of non-meat products like eggs and milk appears to be more viable (Burton, 2019). Companies producing egg and milk substitutes by cellular fermentation are predicted to have products on the market over the next one to two years. This may spur further investment in the sector. Additionally, the risk of zoonotic disease, and awareness around the risk of future pandemics derived from intensive poultry or pork, could result in greater public and private investment.

The Current State of the Technology

This industry is supported by the rise in sales of vegetarian and vegan products in the UK. Awareness of the negative externalities associated with the livestock sector is leading many to shift to alternative protein sources. This trend has stimulated investment in cellular agricultural technologies.

There are significant challenges to the production of cellular meat, these include the sourcing of appropriate cell lines, the sourcing and composition of culture media, and the development of scaffolds for structuring the growth of cultured meat. Often these inputs are expensive to source and require tissue extracted from living animals, this will cause some ethically minded consumers to question the benefits of the products (Burton, 2019). It is also common practice to add antibiotics and antimitotics to the culture media as well as a host of other growth factors, hormones, vitamins, amino acids, and carbohydrates. Standardised and comprehensive life cycle analysis of these inputs is needed to validate the environmental impact of the processes.

There are also questions as to whether cultured meat will be able to effectively emulate the structure of a piece of muscle such as a steak without being prohibitively expensive. Technology to date is only capable of producing thin layers of muscle tissue. Whether this will be preferred to other meat alternatives is yet to be seen.

The major challenge, however, is upscaling these technologies. Expanding and differentiating cells to produce cultured meat in bioreactors large enough to make cultured meat a commodity is a major challenge facing the sector. If achieved, there are then additional challenges to sourcing raw materials, logistics, regulation, infrastructure, and social acceptance.

These challenged are lower, however, for fermented cellular products such as eggs and dairy; companies developing these non-meat proteins appear to be closer to production and commercialisation (Burton, 2019). This is in part because the technology is already widely used to produce enzymes for various food and non-food products (Waschulin & Specht, 2018). These are proven techniques and established companies already produce these enzymes at scale. Hence, it would be feasible for these companies to pivot into cellular fermentation of non-meat proteins. That said, production would be limited by the current lack of bioreactor capacity and considerable scaling would be required to meet an impactful proportion of the demand (Burton, 2019).

Whilst companies may struggle to produce a like-for-like egg using cellular fermentation, it will be less challenging to produce analogous egg and milk compounds. If price parity is reached, these compounds could effectively replace the use of these animal products in the industrial production of a huge range of food products. This could substantially disrupt the market for industrially farmed eggs and milk. Additionally, it will be less likely to compete with the comparatively more extensively farmed fresh eggs and milk bought by the public. In this case, cellular fermentation would support more extensive agroecological production.

A challenge to cellular fermented animal products relates to future regulations for GMOs. Cellular fermentation relies on GE organisms. This may limit the viability of these products in countries like the UK with restrictive regulations on the use of GMOs. Standards and regulations around labelling of GMOs would also have an impact on the size of the market for these products.

There are many start-up companies in the cellular agriculture sector. Some of which are trialling and even selling products. Most notably, in 2020 Eat Just Inc. was granted regulatory approval to produce and sell lab-grown chicken meat in Singapore[36]. This is likely to influence regulation in other nations and increase the interest and investment in the cellular meat sector.

Besides Eat Just Inc., there are a host of companies trying to commercialise cellular meat. These include Memphis Meats[37], Finless Fish[38], and Future Meat[39] in the US. In the UK, these include Higher Steaks[40], Cellular Agriculture Ltd[41], and Multus Media[42]. Companies such as Perfect Day[43] are producing dairy alternatives using cellular fermentation. None of these companies has reached commercialisation yet although several have prototypes, and some have tentatively proposed launch dates. The companies are presumably sustained by venture capital and grants. Few websites clearly show images of products or any concrete information about their viability.

There is considerable uncertainty around the future of the sector and how feasible it is going to be to overcome the challenges and scale the technologies. This has led leading thinkers in the field to call for more open science and public investment in the sector[44]. This would help validate or disprove claims and build a more solid foundation for the sector to develop more effectively. This openness is likely limited by the drive for commercialisation and secrecy within the industry. Based on current technology and research, cellular fermentation of non-meat products is likely to have a substantial impact over the next ten years. Substantial impact and scaling of the cellular meat industry over the same period appears less likely and more uncertain.

Opportunities for Agroecology

Cellular agriculture may support the trend towards agroecology by reducing the pressure on the food system to provide cheap animal protein. Given that processed chicken will be one of the easier meats to culture, there is potential for cultured chicken to reduce demand for intensive chicken farming. Cellular fermentation will likely provide alternative sources of eggs and milk for a variety of food products. This could enhance animal welfare, reduce GHG emissions, lower risk from disease and antibiotic resistance, and reduce water consumption.

Cultured meat may also provide new opportunities within traditional breeding as cell harvesting from these species could be more attractive to cultured meat producers (Stephens et al., 2018). Hence there is a possibility to partner cultured meat producers with extensive agroecological farmers. If communicated well this may garner support for agroecological production from cellular meat consumers.

36 https://www.foodsafetynews.com/2020/12/eat-just-inc-gets-approval-in-singapore-for-lab-grown-chicken/
37 https://www.memphismeats.com/making-meat
38 https://www.finlessfoods.com/
39 https://future-meat.com/
40 https://www.highersteaks.com/
41 https://www.cellularagriculture.co.uk/
42 https://www.multus.media/
43 https://perfectdayfoods.com/
44 https://www.nature.com/articles/d41586-020-03448-1

Cultured meat may also be more suited to decentralised local production. This may reinforce local supply chains also benefiting agroecological farmers.

Risks for Agroecology

It is important to ensure the cell culture, inputs, and waste products do not lead to hidden environmental damage. Many current cellular agricultural products use animal products such as foetal serums and embryonic extracts and add antibiotics, growth factors, and hormones to the culture media. The sourcing and disposal of these materials should be ethical, transparent, and factored into the environmental footprint of the products through complete life cycle analysis.

If scaled, there would be considerable social impacts from cellular agriculture. Jobs would shift with more jobs for higher educated groups such as engineers, microbiologists, and food technologists, and fewer jobs, particular amongst less-educated groups. This would be politically and socially volatile and would need to be carefully managed.

If cellular meat cannot achieve a competitive price with cheaper, processed animal products, there is a risk that it will be marketed as an alternative to agroecological animal products. This could restrict the market for livestock that plays an important role in nutrient cycling on agroecological farms. Contrastingly, if the cellular agriculture sector continues to grow, increased meat industry lobbying is likely. The industry may promote a greater focus on the efficiency of intensive production, shifting public understanding and support away from agroecological farmed animal products.

5.2 Controlled Environment Agriculture

Controlled environment agriculture is a form of food production that takes place in enclosed growing structures such as greenhouses and buildings. Methods include aquaponics, hydroponics, and aeroponics.

Vertical and urban farms often use controlled environment agriculture. These systems offer ways to produce commercial quantities of crops close to and within urban environments. If scaled, this has benefits for food security and nutrition.

Controlled environment agriculture systems can reduce water use by up to 95%, produce all year round, eliminate transport costs, improve food safety and biosecurity, and substantially reduce reliance on pesticides, herbicides, and fertilisers. For certain crops, vertical farms are more than twenty times more productive than conventional farms in the equivalent area (Benke & Tomkins, 2017; Lumpur, 2018).

Promoters of the technology aim to significantly increase food production in urban environments by producing substantial quantities of food in high rise urban farms that stack layers of crops grown in highly regulated, productive, sustainable, and automated systems (Benke & Tomkins, 2017). Breakthroughs in automation, machine learning, image recognition, and robotics will enable the highly efficient production of crops powered by renewable energy.

Scenario Analysis of Cellular Agriculture

	Consolidated control	Equitable food system
Agroecological diverse food production	Certain cellular agricultural products such as milk and eggs are developed and scaled. However, only a few corporate actors have control over a largely automated production process. This leads to consolidated control of a substantial segment of the protein production sector and a reduction in the number of jobs. Fears about intellectual property rights and the drive to disrupt the livestock sector led many start-ups to make unvalidated and grandiose claims. The absence of collaboration causes growth in the sector to stall, investment to dry up, and interest in cellular agriculture to falter.	Public and private sector collaboration helps validate the potential of the cellular agricultural sector. Full lifecycle analysis is incorporated into product production and communicated to actors across the supply chain, building trust in the sector. Technologies are optimised and scaled to replace certain forms of processed animal products. More broadly cellular agriculture becomes a standardised and accepted protein source for consumers. It is accepted as an alternative protein source alongside plant-based meat alternatives. Cellular agriculture substantially reduces the environmental and animal welfare issue associated with chicken, egg, and dairy production. These products help consumers shift to less environmentally damaging diets and they enhance the flavour of meat analogues. The sector sources cells from agroecological sources and communicates the benefit of this type of agriculture.
Intensive agriculture	High price tags on cellular meat cause companies to market products as alternatives to high value agroecological animal products. Promotion campaigns present agroecological animal production negatively. Competition between the two forms of production enhances a negative conception of agroecological livestock production.	Cellular agriculture production is optimised, and the cost of production is lowered enough to provide a healthier, more sustainable form of meat to a wide range of socio-economic groups. However, resources and cells for culture media are sourced from non-sustainable sources. Cellular agriculture companies promote a negative attitude towards all forms of livestock farming. This suppresses the market for and understanding of agroecological animal products.

Two main factors influence the scale of impact the sector will have. Firstly, how cost-effective can production be made. Controlled environmental agriculture has high start-up costs; proximity to urban markets often means high property costs, investment in the technology is high, and energy costs, if not provided off-grid, can be a barrier.

The second factor relates to whether the technology can be made suitable for growing a wide range of crops. This relates to the first issue, in that it is assumed most crops can be grown using these techniques, but it is questioned whether it is economically viable. Completely shifting food production to vertical production is unfeasible as the lighting alone would require huge amounts of power. Whilst efficiencies will go some way to tackling this issue, the energy costs of controlled environment agriculture are a major constraint on its scalability.

Whilst it is doubtful as to whether controlled environment agriculture will ever provide a viable method for producing staples such as grains, root vegetables, and rice, these systems will and are providing fresh produce such as leafy greens, herbs, tomatoes, and strawberries. Whether they manage to overcome the barrier of high start-up costs to provide a cost-effective food source and not a niche high-value supply of fresh produce, is yet to be seen (Beacham et al., 2019). It has also been noted that there is a sparsity of well-validated research and data in this sector making predicting impact and viability difficult (Beacham et al., 2019).

The Current State of the Technology

At this point, controlled environment agriculture, and particularly vertical urban farming, is a tiny and largely unprofitable sector, occupying the equivalent of 30 hectares worldwide[45]. It is predominantly growing leafy greens and herbs. These crops are small, grow quickly, transport poorly, and can be sold at a premium (Benke & Tomkins, 2017). This suits them to controlled environmental agriculture. The price premium and quick harvesting mean they are better suited to offsetting high start-up costs.

It is predominantly breakthroughs in the efficiency and cost of LED bulbs that have increased the viability of controlled environment agriculture. Advances in electronics, automated environmental control, solar, wind power, and computing power have also aided development (Benke & Tomkins, 2017).

Singapore has, one of the most established controlled environmental agricultural sectors, producing 10% of leafy vegetables with these methods. This has, in part, been driven by a desire to improve food security and reduce reliance on imports. Vegetables grown in these vertical systems cost only 10% more than those imported. Across the world companies are establishing varying scale projects, some combine growing with aquaculture, producing fish as well, but the vast majority focus on the production of leafy greens and herbs and target premium, niche markets.

The challenges have not deterred investment and development in the sector. The world's largest vertical farm is currently under construction in Abu Dhabi, the technology may be particularly beneficial for water-poor energy-rich countries. At the same time, Nordic Harvest[46] is constructing one of Europe's largest vertical farms and claims it will be profitable within its first year.

45 https://www.ft.com/content/0e3aafca-2170-4552-9ade-68177784446e
46 https://www.nordicharvest.com/

Cultured meat being produced in a laboratory

Getty

In the UK, Jones Food Company[47] is one of the largest controlled environment agricultural companies. They produce a range of crops including kale, radish, and parsley. Growing Underground[48] is a London enterprise that supplies high-end salad mixes and microgreens from disused underground tunnels.

Despite the high levels of interest in the sector, it currently remains niche, providing premium products to those who can afford it. Evidence about the financial viability and sustainability of companies is minimal and largely based on claims made by the industry. There is a need for academic research and collaboration in the sector to better understand the role it will play in future food systems (Beacham et al., 2019).

Opportunities for Agroecology

There is potential for controlled environment agriculture to support agroecological farming by reinforcing localised supply chains and reducing dependence on imports. Moreover, the area may be spared from intensive farming. Producing crops in controlled environment agricultural systems could free up space for lower-yielding agroecological farming systems delivering public goods.

Controlled environment agriculture businesses would benefit from environmental labelling as it would provide a selling point for their produce. They could, therefore, help support regulations that enforce labelling and traceability which would also benefit agroecology. In this way synergies between controlled environment agriculture product labelling and supply chains and those of agroecological products could encourage agroecological consumption.

47 https://www.jonesfoodcompany.co.uk/
48 http://growing-underground.com/

Scenario Analysis for Controlled Environment Agriculture

	Consolidated control	Equitable food system
Agroecological diverse food production	The desire for market dominance causes organisations to maintain high levels of secrecy. This stifles collaboration and research and leads to many inefficient enterprises failing to reach economic viability. Moreover, a lack of optimisation and research means production remains high cost and products are only affordable to wealthier consumers. Companies that do manage to scale dominate the sector but are resistant to collaboration and tend to operate behind closed doors. This limits the social benefit of the operations.	Controlled environment agriculture helps reduce imports of certain kinds of vegetables by providing year-round production. The sector helps strengthen local supply chains which also benefit agroecological growers. Companies in the sector help support a drive for environmental labelling of foods which helps support sustainable agricultural practice. The sector enhances its viability through collaboration with the public sector and research institutions. This helps reassure investors and create a viable controlled environment agricultural sector in the UK. Companies in the sector also strive to enhance urban understanding of natural cycles through educational visits, workshops, and employment. Public support is provided for companies seeking to produce fresh produce in disadvantaged areas. These projects help raise awareness around nutrition in these communities.
Intensive agriculture	The sector fails to scale and poorly substantiated claims cause investors to lose faith in the sector. The embodied carbon in the infrastructure used by the companies means the sector fails to have a positive environmental impact.	NA

5.3 Bioenergy Production

Bioenergy refers to electricity, gas, and fuel that is generated from organic matter, known as biomass. This includes plants, timber, sewage, agricultural, and food waste (Soil Association, 2020).

Globally, bioenergy production is predicted to more than quadruple by 2040 (Correa et al., 2019). How this bioenergy is produced will determine the scale of the environmental impact.

Bioenergy can be produced in various ways, most commonly through the combustion of wood pellets and the anaerobic digestion of biodegradable materials to produce biogas. Biofuel production is more complex as it requires the biomass to be converted into a liquid form.

First-generation bioenergy is produced from crops. This is the most validated and widely utilised production method for bioenergy and biofuel. However, it is widely considered environmentally detrimental, often exhibiting higher levels of environmental harm than conventional fuels. It competes with land for food and habitat driving up food and land prices and impacting biodiversity. Moreover, the production of energy crops like maize can consume considerable resources, degrade soils, and reduce habitat availability. The expansion of first-generation biofuel has largely been down to its low cost which has been supported by subsidies.

Second-generation bioenergy is posited as a solution to many of the issues associated with first-generation bioenergy. This is because they are produced from non-edible crop residue. The high costs of converting lignocellulosic residues into biofuel, however, reduce its economic competitiveness (Correa et al., 2019).

Third generation biofuels are mainly made from microalgae. The hope is that microalgae biofuel can be produced in huge ponds and bioreactors, sequestering carbon, and recycling nutrients. This almost completely removes the issues associated with land conflict. Algae have been proposed as appropriate for biofuel production because they exhibit higher photosynthetic efficiency than plants; faster growth rates; are richer in lipids than conventional oil crops; and contains next to no recalcitrant lignin (Raheem et al., 2018). However, the sector faces significant challenges. Scalability, operational stability, and cost all impose potentially insurmountable barriers.

Overall, there is a risk that the bioenergy sector is being kept alive by alignment with fossil fuel infrastructure, subsidies, and a failure of the industry to confront the full extent of its environmental and social impacts. There is a need to integrate robust assessments of these impacts into the sector to increase transparency and awareness and stimulate more informed decision making (Correa et al., 2019). This should be used to reassess and remove many of the perverse subsidies that are keeping unsustainable and inefficient production methods in the bioenergy sector afloat.

The Current State of the Technology

Most global biofuel production is first-generation, with the associated environmental, social, and economic impacts. This has often been stimulated by subsidies. In countries such as Germany, this has led to rapid growth in maize production for Anaerobic Digestion increasing land prices and reducing food production profitability (Soil Association, 2020). In the UK, maize has been a core feedstock for anaerobic digestion due in part to its high energy yield. In 2017, 31% of the UK maize crop was for energy leading to substantial soil degradation (Soil Association, 2020).

In 2018, bioenergy accounted for approximately 7% of the UK's primary energy supply. This means biomass is the largest source of renewable energy in the UK, accounting for almost 40% of the total. The supply of bioenergy is predicted to increase as demand for non-fossil fuel-based energy grows[49]. Half of this bioenergy is produced from the combustion of imported wood fuel at Drax power station, a former coal power plant. Drax has received considerable subsidies. However, the environmental footprint of sourcing and transporting the wood has led many to doubt its environmental sustainability. Even when harvested wood is replaced it takes many years to sequester the carbon again meaning activities, even when optimal create a carbon debt that might jeopardise climate goals.

The reliance on biomass in the UK and across the globe is due to its ability to provide a consistent baseload power resource. This can balance out the fluctuations in power from renewables. Additionally, biomass can be used to produce liquid and gas fuels that fit into current infrastructures for heating and transport.

The desire to produce greener biofuels led to a boom of investment in algal biofuels at the start of this millennium. However, the challenges to scale and reach economic viability led many of these companies to shift into the production of alternative products and many high-profile investors such as Shell to abandon their investments. However, certain companies like Synthetic Genomics[50] are still working on biofuel production. They have a long-standing partnership with ExxonMobil and are looking to produce 10,000 barrels of oil per day by 2025[51]. With these time frames and the challenges facing the sector, it seems unlikely that algae will play a significant role in bioenergy production over the next ten years.

Opportunities for Agroecology

Biomass sales can provide additional revenue for agroecological farmers through the sale of waste materials and woody biomass. The revenue from this woody biomass may increase the economic viability of agroforestry systems. Small scale bioenergy production on farms can improve profits by reducing energy costs and enabling excess energy to be sold to the grid. This can also lower the carbon footprint of farms.

Risks for Agroecology

There is a risk that incentivising farmers to sell organic material as biomass could prevent this material from being returned to the soil as organic matter. Moreover, market demand for biofuel crops can incentivise more intensive production of biomass. This would reduce the capacity for low yield, low impact production systems like agroecology. This has been seen in several countries including Germany. Likewise, public support for large scale anaerobic digestion of manure could create incentives for large-scale industrial livestock units.

49 https://www.ons.gov.uk/economy/environmentalaccounts/articles/aburningissuebiomassisthebiggestsource ofrenewa-bleenergyconsumedintheuk/2019-08-30
50 https://syntheticgenomics.com/
51 https://corporate.exxonmobil.com/Energy-and-innovation/Advanced-biofuels/Advanced-biofuels-and-algae-re-search#Biofuelsresearchportfolio

Scenario Analysis of Bioenergy Production

	Consolidated control	Equitable food system
Agroecological diverse food production	NA	Well-regulated life cycle analysis of bioenergy production is enforced and helps decision-makers make informed decisions about the consequences of bioenergy. This information must be made publicly available. Investment and subsidisation of the bioenergy sector decline as awareness around the associated externalities grow. The bioenergy sector declines, particularly at a large scale. Most remaining projects are small scale and function at the farm level where they help farmers utilise waste and produce energy on-site. These small-scale projects also help support agroforestry projects.
Intensive agriculture	Investment and subsidisation in the bioenergy sector continues and incentivises increased production of biomass on farms. This increases pressure on land and rises land and food costs. This impacts the availability of local produce and restricts access to the agricultural sector. Growth in biomass production drives landowners to monocultural production and increases environmental degradation. Failure to enforce accurate lifecycle analysis and transparency in the sector means public awareness of environmental damage is low. This means there is little pressure on the sector to increase its sustainability. Investment in bioenergy production leads to intensified production on the remaining available agricultural land. There is little space for agroecological production, particularly as inflated land prices mandate high yield, high profit agriculture.	NA

6. Governance Principles and Recommendations for AgroEcoTech

Up to this point, risks, opportunities, and scenarios had been defined for each separate technology category. These highlighted likely and evidence-based ways that the technologies might be designed, developed, and adopted to either align or conflict with the ten elements of agroecology (FAO, 2018).

For each scenario analysis it was possible to use the risks and opportunities to define projections where the technology may either entirely conflict with the elements of agroecological; align only with the social elements; align only with the ecological elements; or, at least to a degree, align with the social and ecological elements.

By reviewing the various predictions about the future role of each technology, by interviewing and meeting with an expert advisory panel, and by undertaking a co-design workshop with agroecology aware farmers (See Appendix 1 for a summary of the workshop) it was possible to draw out commonalities between the risks, opportunities, and scenarios. There were key findings that appeared in multiple sections that could reduce the risks and maximise the opportunities for agroecological transition. It was these insights that were identified, extracted, summarised, discussed, and refined into the governance principle that are listed below.

Although some of these governance principles clearly relate to certain technology categories more than others, they are mostly cross-cutting. They identify principles that should be followed so that the decision making around these technologies is structured in a way that increases the opportunities they will provide for agroecological transition. In this sense the principles are directly related to governance.

The definition of governance varies depending on the context in which the term is used. For this report, the definition provided by the United Nations Development Programme (UNDP) was found to be most relevant and has been used. The UNDP define governance as

> the system of values, policies and institutions by which a society manages its economic, political and social affairs through interactions within and among the state, civil society and private sector. It is the way a society organizes itself to make and implement decisions—achieving mutual understanding, agreement and action. (UNDP, 2004, p. 2)

In line with this definition, the governance principles below attempt to provide keyways that interactions between the state, civil society and the private sector can be organised and structured to make decisions that support the development and use of agroecology supportive technology.

This is not an exhaustive list and each of the principles would need considerable research, development, and refinement before they could be operationalised. However, they provide a broad and thorough foundation for understanding and further developing a technology governance landscape that can support agroecological transition in the UK.

The twelve principles are listed below. They are grouped into three categories based on the aspect of good governance that they relate to. The categories are participatory knowledge generation, accessibility and equity, and accountability and transparency.

6.1 Participatory Knowledge Generation

1. Agroecology necessitates the development of knowledge sharing networks that facilitate peer-to-peer learning between farmers, and between actors and researchers operating across the supply chain. The public sector should provide funding and regulation that supports technological innovation that facilitates this learning through the development of smart farming networks.

2. Regulation must ensure that data collected on a farm must be made available to the farmer in an accessible format. Farmers must have the rights to seek third party advice on the interpretation of this data.

3. Agricultural advice on the use of technology is too often left to companies with incentives to perpetuate conventional, input-intensive farming. Impartial advice rooted in good agroecological practice needs to be made available and promoted. The UK government should fund the development and dissemination of resources informing farmers about good agroecological practice. It should be mandated that all agricultural companies need to connect farmers to these resources when selling products. The aim is to avoid these companies controlling the advice given to farmers and to provide farmers with a way to validate the claims made by companies. Resources should also provide farmers with contacts where they can seek further impartial advice.

4. The UK education sector, and particularly universities, should encourage agroecological food system innovation. For example, competitions in engineering universities could encourage students to work collaboratively with agroecological farmers to design innovative robots.

5. Interdisciplinarity is key to the development of effective agricultural technology. Farmers must be involved in technology design, not just consulted on adoption. Development and testing should take place on real agroecological farms with real farmers. Public sector grants should necessitate farmer involvement and universities and research institutes should prioritise researcher-and-farmer collaboration.

6. Collaboration between academia and companies developing high profile disruptive technologies should be prioritised to improve the viability and validate claims. Attractive grants that necessitate collaboration and are considerate of issues surrounding intellectual property should be developed by the UK government.

6.2 Accessibility and Equity

7. Access to sustainability enhancing technology, and particularly data gathering solutions, should be maximised across all scales of agriculture. Regulation should be restructured, and incentives put in place to encourage companies to develop innovative modular, flexible, interoperable technologies accessible through rental and service-based schemes. This will increase access to cutting edge agricultural technologies.

8. All actors should have the right to repair and adapt technology that they own. Standards and regulations should enhance repairability and interoperability. Modularity and adaptability should be encouraged.

6.3 Accountability and Transparency

9. Technology should be adapted to accommodate the diversity of good agroecological systems, agricultural systems should not be adapted for technology. The UK government should appoint or identify an interdisciplinary board to use the defined core features of good agroecological systems to create a framework for reviewing new crop varieties and public investment in technologies. This framework should be used to guide development, policies, grants, subsidies, and investments.

10. The same interdisciplinary board should be appointed by the government to develop an integrated form of cost-benefit analysis incorporating predicted environmental and social aspects. This analysis tool should be factored into public and private investment decisions in the food sector. Investments found to have substantial predicted environmental and social costs should be restricted. This integrated cost-benefit analysis would also reveal opportunities that could have substantial environmental and social benefits but have low market value. The UK government should establish mechanisms to support such opportunities.

11. The UK government should enforce the development and integration of standardised, thorough, and transparent lifecycle analysis across all large industries and encourage uptake in developing sectors. The lifecycle analysis procedures should be developed by third-party interdisciplinary bodies and not by the industry.

12. Regulation should ensure reviews of new crop varieties, key performance indicators of public sector investment, and life cycle analysis of technologies are made publicly available and communicated in an accessible manner. This should give the public a chance to provide feedback, which should be considered during decision making.

7. Indicators for Good Governance of AgroEcoTech

Defining principles for AgroEcoTech governance provides the foundation for how decision making should be structured. However, to understand how effectively these principles are being incorporated into decision making and to map trends in the uptake of the principles and the impacts it is important to be able to record and measure them.

Given that the principles are broad, qualitative, and multifaceted, it is impossible to measure them directly. Instead, proxy indicators are needed to measure the degree to which each principle is being adhered to.

As with the principles themselves, these indicators are not exhaustive or operational. Instead, they provide a range of potential metrics and questions that could be answered to quantify the effectiveness of AgroEcoTech governance. Below we provide some select indicators that could provide insights into the scale of implementation of each principle. A more expansive list of potential indicators is provided in Appendix 2. These indicators are intended to provide the foundation for further research and development. Individually they say little about the effectiveness of AgroEcoTech governance, but if refined, combined, and developed into a framework for reviewing AgroEcoTech governance they will provide a valuable assessment tool. Further work to develop this framework is recommended.

7.1 Indicators of Participatory Knowledge Generation

1. Number of multidisciplinary collaborative research projects involving farmers on farms.
2. Scale of investment and development of open-source farmer to farmer knowledge and data sharing platforms.
3. Farmer opinion on and willingness to share data (evaluated by number of complaints to government departments, number of lawsuits).
4. The number and scale of public data sets considered accessible and usable for a UK farmer.
5. Percentage of farmers accessing impartial agroecological advice.
6. The number of UK universities/ agricultural colleges with programmes teaching about agroecology and agroecological food system innovation.

Innovative Farmers

Anthony Snell with RootWave's tractor mounted electrical weeding machine which he was testing on his top fruit farm as part of an Innovative Farmer's field lab

7.2 Accessibility and Equity

7. Number of technology rental and sharing schemes.
8. Average farm expenditure on various categories of technologies.
9. Presence of standards and regulation to enhance repairability, interoperability, and modularity.
10. Number of farmer complaints about lack of interoperability of certain types of technology.

7.3 Accountability and Transparency

11. Presence of a system to review public/ private investment in agricultural technology based on alignment with agroecological principles.
12. Presence of policies mandating standardised lifecycle analysis methodology.
13. Presence of a clear procedure for allowing the public to contribute to the review of public investment in agricultural technologies.
14. Number of government-led co-design workshop between actors in the food sector and the public.

8. Discussion

Drawing on the assessment of the various technologies, it is cautiously possible to propose the types of technologies that should be prioritised for supporting an agroecological transition in the UK. To do this, we propose two new groups of technologies that should be prioritised sequentially.

The first group is the one we believe is initially most important for supporting an agroecological transition. It includes technologies for remote sensing of environmental impact, big data analysis for environmental footprint accounting, and dynamic food procurement. These technologies and the wider group of innovations and research that surround them enable the creation of a food system that is more supportive of agroecology. Carbon monitoring and payments, biodiversity monitoring, reduced cost certification, green investment, local supply chains, transparency and traceability can all be enhanced by these technologies. If developed correctly, they can help agroecological food production become a more attractive alternative to actors across the food chain.

The second group relates to technologies that can support a more efficient and less labour-intensive form of agroecology. Smart agricultural technologies, robotics, and novel biological controls and inoculants make up this group. All can accelerate an agroecological transition by making it a more reliable and viable option for farmers considering a transition and for those already practising agroecological farming. It is the first group of technologies that will create the demand for and stimulate investment in these technologies. In turn, this second group of technologies will reinforce agroecology as an increasingly attractive form of food production for farmers of all scales.

The principles and tests we have proposed are a step towards reviewing technological developments, such as those described in this discussion, and to ensure these developments support the agroecological transition. They are far from complete but provide an example and a foundation for how future decision-makers might review their support of technologies. If technology is going to support an agroecological transition, it is essential that these principles and tests are developed and integrated into decision making and used to enhance the governance of agroecological technologies.

Alongside these technologies, however, there needs to be a mindset shift across the food supply chain. Actors need to: collaborate and think systemically; be observant and receptive to natural cycles; and listen and respond to the feedback of actors across the supply chain. We need to think less in terms of singular solutions to specific issues, and more in terms of small tweaks to systems that guide agricultural systems towards greater integrated sustainability and agroecological alignment. All actors need to comprehend innovations not as singular solutions but as tools that can respond to a system in flux, an increasingly diverse system. A more natural system.

References

Altieri, M. A. (1989). Agroecology: A New Research and Development Paradigm for World Agriculture. Agriculture, Ecosystems and Environment. Elsevier.

Askary, T. H., & Abd-Elgawad, M. M. M. (2021). Opportunities and challenges of entomopathogenic nematodes as biocontrol agents in their tripartite interactions. Egyptian Journal of Biological Pest Control.

Audsley E, Brander M, Chatterton J, et al., (2009). How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. WWF-UK.

Baltes, N. J., Gil-Humanes, J., & Voytas, D. F. (2017). Genome Engineering and Agriculture: Opportunities and Challenges. Progress in Molecular Biology and Translational Science. Elsevier.

Barriuso, A. L., González, G. V., De Paz, J. F., Lozano, Á., & Bajo, J. (2018). Combination of multi-agent systems and wireless sensor networks for the monitoring of cattle. Sensors (Switzerland).

Barrows, G., Sexton, S., & Zilberman, D. (2014). Agricultural biotechnology: The promise and prospects of genetically modified crops. Journal of Economic Perspectives.

Beacham, A. M., Vickers, L. H., & Monaghan, J. M. (2019). Vertical farming: a summary of approaches to growing skywards Vertical farming. The Journal of Horticultural Science and Biotechnology. Taylor & Francis.

Behmann, J., Acebron, K., Emin, D., Bennertz, S., Matsubara, S., Thomas, S., Bohnenkamp, D., Kuska, M. T., Jussila, J., Salo, H., Mahlein, A. K., & Rascher, U. (2018). Specim IQ: Evaluation of a new, miniaturized handheld hyperspectral camera and its application for plant phenotyping and disease detection. Sensors.

Benke, K., & Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. Sustainability: Science, Practice and Policy. Taylor & Francis.

Benton, T. G., Bieg, C., Harwatt, H., Pudasaini, R., and Wellesley, L. (2021). Food system impacts on biodiversity loss: Three levers for food system transformation in support of nature. Chatham House.

Berti, G., & Mulligan, C. (2016). Competitiveness of Small Farms and Innovative Food Supply Chains: The Role of Food Hubs in Creating Sustainable Regional and Local Food Systems. Sustainability. MDPI.

Boeraeve, F., Dendoncker, N., Cornélis, J. T., Degrune, F., & Dufrêne, M. (2020). Contribution of agroecological farming systems to the delivery of ecosystem services. Journal of Environmental Management.

Burton, R. J. F. (2019). The potential impact of synthetic animal protein on livestock production: The new "war against agriculture"?. Journal of Rural Studies

Correa, D. F., Beyer, H. L., Fargione, J. E., Hill, J. D., Possingham, H. P., Thomas-hall, S. R., & Schenk, P. M. (2019). Towards the implementation of sustainable biofuel production systems. Renewable and Sustainable Energy Reviews. Renewable and Sustainable Energy Reviews. Elsevier.

Chen, M., Arato, M., Borghi, L., Nouri, E., & Reinhardt, D. (2018). Beneficial services of arbuscular mycorrhizal fungi – from ecology to application. Frontiers in Plant Science.

Department for Business, Energy & Industrial Strategy. (2019). 2017 UK Greenhouse Gas Emissions, Final Figures.

Dukare, A., Paul, S., Kumar, R., & Sharma, V. (2021). Microbial-based inoculants in sustainable agriculture: Current perspectives and future prospects. In Biofertilizers. Elsevier Inc.

EFSA Panel on Genetically Modified Organisms (GMO) (2012) Scientific opinion addressing the safety assessment of plants developed through cisgenesis and intragenesis. EFSA Journal

FAO. (2018). The 10 elements of agroecology. FAO.

Francis, C. A., Gliessman, S. R., Lieblein, G., & Salomonsson, L. (2003). Agroecology: The Ecology of Food Systems. Journal of Sustainable Agriculture.

Hardin, P. J., Lulla, V., Jensen, R. R., Jensen, J. R., Hardin, P. J., Lulla, V., Jensen, R. R., & Small, J. R. J. (2018). Small Unmanned Aerial Systems (sUAS) for environmental remote sensing: challenges and opportunities revisited. GIScience & Remote Sensing.

Hebrok, M., & Boks, C. (2017). Household food waste: Drivers and potential intervention points for design - An extensive review. Journal of Cleaner Production. Elsevier.

Hyde, K. D., Xu, J., Rapior, S., Jeewon, R., Lumyong, S., Niego, A. G. T., Abeywickrama, P. D., Aluthmuhandiram, J. V. S., Brahamanage, R. S., Brooks, S., Chaiyasen, A., Chethana, K. W. T., Chomnunti, P., Chepkirui, C., Chuankid, B., de Silva, N. I., Doilom, M., Faulds, C., Gentekaki, E., … Stadler, M. (2019). The amazing potential of fungi: 50 ways we can exploit fungi industrially. Fungal Diversity.

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany.

Kamilaris, A., Fonts, A., & Prenafeta-bold, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. Trends in Food Science & Technology. Elsevier.

Kamilaris, A., Kartakoullis, A., & Prenafeta-boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture.

Kaminsky, L. M., Trexler, R. V., Malik, R. J., Hockett, K. L., & Bell, T. H. (2019). The Inherent Conflicts in Developing Soil Microbial Inoculants. Trends in Biotechnology.

Klemas, V. V. (2015). Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview

Klümper, W.; Qaim, M. (2014). A meta-analysis of the impacts of genetically modified crops. PLoS ONE

Krishna, Vijesh & Qaim, Matin & Zilberman, David. (2015). Transgenic crops, production risk and agrobiodiversity. European Review of Agricultural Economics.

Lampridi, M. G., Kateris, D., Vasileiadis, G., & Marinoudi, V. (2019). A Case-Based Economic Assessment of Robotics Employment in Precision Arable Farming. Agronomy. MDPI.

Lotz, L. A. P., van de Wiel, C. C. M., & Smulders, M. J. M. (2020). Genetic engineering at the heart of agroecology. Outlook on Agriculture. Sage.

Lowenberg-deboer, J., Behrendt, K., Godwin, R., & Franklin, K. (2019). The Impact of Swarm Robotics on Arable Farm Size and Structure in the UK. Harper Adams University, Newport, Shrophire, UK Contributed Paper prepared for presentation at the 93.

Lumpur, K. (2018). Opportunities and Challenges in Sustainability of Vertical Farming: A Review. Journal of Landscape Ecology. De Gruyter.

Marec, F., & Vreysen, M. J. B. (2019). Advances and challenges of using the sterile insect technique for the management of pest lepidoptera. Insects.

Mattick CS, Landis AE, Allenby BR, Genovese NJ. (2015). Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States. Environ Sci Technol.

Mann, C. C., & Pinchot, B. (2018). The wizard and the prophet: two remarkable scientists and their duelling visions to shape tomorrow's world. Pan Macmillan.

National Academies of Sciences, Engineering, and Medicine. (2016). Genetically Engineered Crops: Experiences and Prospects. Washington, DC: The National Academies Press.

Nigel Dudley & Sasha Alexander (2017) Agriculture and biodiversity: a review, Biodiversity

Pretty, J. N., Noble, A. D., Bossio, D. A., Dixon, J. (2006). Resource-Conserving Agriculture Increases Yields in Developing Countries Policy Analysis. Environmental Science & Technology. American Chemical Society.

Poux, X., Aubert, P.-M. (2018). An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise, Iddri-AScA.

Raghavan, B., Norton, J., Tomlinson, B., Nardi, B., Lovell, S. T., Patterson, D. J. (2016). Computational Agroecology: Sustainable Food Ecosystem Design.

Raheem, A., Prinsen, P., Vuppaladadiyam, A. K., Zhao, M., & Luque, R. (2018). A review on sustainable microalgal based biofuel and bioenergy production: Recent developments. Journal of Cleaner Production. Elsevier.

Regalado, A. (2019). Gene-edited cattle have a major screwup in their DNA. MIT Technology Review. Retrieved May 24, 2021 from. https://www.technologyreview.com/2019/08/29/65364/recombinetics-gene-edited-hornless-cattle-major-dna-screwup/

Santos, M. S., Nogueira, M. A., & Hungria, M. (2019). Microbial inoculants: reviewing the past, discussing the present and previewing an outstanding future for the use of beneficial bacteria in agriculture. AMB Express.

Shakhbulatov, D., Arora, A., Dong, Z., & Rojas-cessa, R. (2019). Blockchain Implementation for Analysis of Carbon Footprint across Food Supply Chain. IEEE International Conference on Blockchain (Blockchain)

Smetana, S., Mathys, A., Knoch, A., & Heinz, V. (2015). Meat alternatives: life cycle assessment of most known meat substitutes. International Journal of Life Cycle Assessment.

Smyth, S., Gusta, M., Belcher, K., Phillips, P., & Castle, D. (2011). Changes in Herbicide Use after Adoption of HR Canola in Western Canada. Weed Technology

Soil Association. (2020). Bioenergy - Evidence Summary and Review. Unpublished.

Sprink, T., Eriksson, D., Schiemann, J., & Hartung, F. (2016). Regulatory hurdles for genome editing: process- vs. product-based approaches in different regulatory contexts. Plant Cell Reports.

Stephens, N., Di, L., Dunsford, I., Ellis, M., Glencross, A., & Sexton, A. (2018). Trends in Food Science & Technology Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture. Trends in Food Science & Technology. Elsevier.

UKRAS (2018). Agricultural Robotics: The Future of Robotic Agriculture.

UNDP. (2004). Governance Indicators: A Users' Guide. United Nations Development Programme.

USGS. (2021). What is remote sensing and what is it used for? https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used?qt-news_science_products=0#qt-news_science_products

Velasova, M., Alarcon, P., Williamson, S., & Wieland, B. (2012). Risk factors for porcine reproductive and respiratory syndrome virus infection and resulting challenges for effective disease surveillance. BMC Veterinary Research.

Wang, L., Ma, Y., Yan, J., Chang, V., & Zomaya, A. Y. (2018). pipsCloud: High performance cloud computing for remote sensing big data management and processing. Future Generation Computer Systems.

Waschulin, V. & Specht, L. (2018). Cellular agriculture: An extension of common production methods for food. The Good Food Institute.

Weersink, A., Fraser, E., Pannell, D., Duncan, E. and Rotz, S. (2018). Opportunities and challenges for big data in agricultural and environmental analysis. Annual Review of Resource Economics.

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. Sustainable Agriculture, 2, 27–43. https://doi.org/10.1007/978-94-007-0394-0_3

Wittman, H., James, D., & Mehrabi, Z. (2020). Advancing food sovereignty through farmer-driven digital agroecology. International Journal of Agriculture and Natural Resources.

Appendix 1: Co-design Workshop

8.1 Aim

A co-design workshop was undertaken towards the end of the project. The aim was to give a wider selection of actors the opportunity to contribute to the assessment of AgroEcoTech, and the formulation of the AgroEcoTech governance principles.

8.2 Method

The participants all had prior experience of agroecology and were predominantly farmers or representatives of organisations that worked with farmers and the food system.

Participants with prior experience and understanding of agroecology were selected to simplify the proceedings and reduce the time needed to introduce the concepts. All the participants were broadly supportive of agroecology. This was deemed necessary given that the report is premised on a desire to support the agroecological transition. However, it is worth noting that selecting participants in this way will have narrowed the perspectives that the workshop could elucidate. Given the time constraints, though, this was considered an optimal solution. If research in the area is continued, it will be important to incorporate the insights of a wider variety of stakeholders including actors such as consumers, wholesalers, and chefs.

At the start of the workshop, participants were briefly introduced to each of the technology groups. The technologies were grouped into three categories to simplify the structure of the workshop. These groups were as follows:

1. Farm production technology – genome editing, novel biological controls and inoculants, smart agriculture, and robotics.

2. Supply chain technologies – digital food hubs and dynamic food procurement, smart consumer technology, and big data analysis and environmental footprint accounting.

3. Alternative production technologies – cellular agriculture, controlled environment agriculture, and bioenergy production.

The workshop structure emulated the structure of the larger report. In the first half of the workshop, the participants were given the opportunity to discuss and identify the risks and opportunities they associated with each of these technology groups. In the second half, they were encouraged to discuss, develop, and share principles for ArgoEcoTech governance.

This process enabled the findings and principles of this report to be tested, validated, and challenged. It allowed the participants to contribute the insights that they had developed through direct experience with agroecological farming and interactions with the technologies.

8.3 Results

The results of the workshop are summarised below. They provide a valuable comparison to the principles identified in Section 6 and should be factored into future discussions and research on the topic of AgroEcoTech.

The remainder of this section summarises the risks and opportunities identified by the participants for each technology category and ends with a summation of the AgroEcoTech principles produced during the workshop.

8.4 Opportunities and Risks of Farm Production Technology

Participants had mixed feelings about the potential of farm production technologies to benefit agroecology. These technologies were generally thought to have a role to play in a transition to agroecology, but this depended on how well they were integrated into a wider system of agroecological farming. Technology was not viewed as essential to the transformation of the system, and in fact could perpetuate lock-in, particularly if these innovations remained siloed and focused on solving simplified issues to standardised systems. People were also concerned about a 'silver bullet' mentality when it came to technology. Many commented that this idea that one technology could provide a solution to the issues of agricultural systems is inherently incompatible with agroecology.

Broadly, participants supported the use of biological controls and inoculants, citing their capacity to enhance soil health and increase the scale and viability of organic farming. Similarly, many people voiced support for the use of robotics to replace dependence on herbicides. Smart agriculture was viewed as a technology for enabling effective decision making and enhance the understanding of soil health.

Participants were more negative about the use of genome edited organisms on farms. Some participants stated that they lacked the necessary knowledge to comment on the issue but did appreciate that there could be benefits from the use of gene edited varieties. Many others viewed the technology as unhelpful, costly, and incompatible with agroecology. Participants were also concerned about technology leading to a deskilling of the sector and worried about the impact of distancing people from farms.

Accessibility and control were also concerning to many participants. They worried about high costs making the technologies inaccessible, and a lack of control over automation and data leaving farmers increasingly exposed to risks they would not be able to manage. Another participant voiced concerns that planned obsolescence and a lack of repairability could leave farmers unable to repair expensive but outdated technologies.

8.5 Opportunities and Risks of Supply Chain Tech

Participants were most supportive of digital food hubs and dynamic food procurement. Technologies that they claimed gave farmers greater power and control over their supply chains; greater market access; and supported greater transparency and trust. There was general support for the use of data to improve environmental footprint accounting as this could expand the demand for agroecology and help communicate its benefits.

People stated fewer risks concerning the technologies, but many people were worried about who would be able to access, control and profit from data collection; there was a fear that this could lead to manipulation and increase market consolidation. In addition, there were concerns that certain supply chain technologies, such as labelling and packaging, could benefit supermarket supply chains more than alternative localised supply chains. Again, people were concerned about how this might consolidate control.

8.6 Opportunities and Risks of Alternative Production Tech

In general, participants were less supportive of these technologies, seeing them more as a distraction than a solution. However, people did state some benefits. One stated benefit was that the production of alternative protein sources, such as algae and insects, could supply more sustainable animal feed. Another benefit was the potential of these alternative production methods to utilise waste streams. Some participants also stated the benefits of controlled environment agriculture for removing the reliance on imported foods. Whilst others cited the positives of cellular meat for reducing the demand for industrial chicken farms. Bioenergy production was seen as a potential positive only if applied at a small scale and as part of a well-functioning agroecological system.

However, the risks people stated greatly outweighed the opportunities. Generally, people thought of these technologies as incompatible with agroecology and an agroecological mindset. People worried that the scaling of lab-grown meat could have negative impacts on crop rotations. Another participant stated concerns that the removal of soil from the food chain could negatively impact the gut microbiomes of consumers. Most people viewed controlled environment agriculture as a technology with limited impact due to high cost and energy requirements. Bioenergy was perhaps the most negatively viewed technology with participants stating severe concerns about the impact of these technologies upon biodiversity, landscape heterogeneity, pollution, and soil health.

8.7 AgroEcoTech Governance Principles

The principles proposed by the participants related to several common themes and they are presented accordingly.

Data principles

- Data need to be accessible and usable by all to expand access to the benefits
- Big business control of data needs to be minimised
- Data should be open source and not owned by companies with narrow commercial interests.

Scale

- Technology development should not only be accessible to large scale farms. Applicability to a range of scales should be considered at all stages of technology development.
- Grants need to be made available to small scale businesses.

Market dynamics

- The market should not be relied upon to support agroecological innovations. It is more likely to support technology suited to large scale agriculture.
- Agroecological innovation should be considered a public good.
- There is a need for market developments that incentivise and enable agroecology
- Markets are currently suited to investing and support generic and large-scale solutions, this makes them poorly compatible with agroecology.

Knowledge

- Agroecology research and education should be focused on the level of the farm.
- There is need for a clear and widely understood definition of agroecology.
- Technology to facilitate peer-to-peer knowledge sharing is key and needs to be made widely accessible.
- Advice based on the principles of agroecology needs to be made widely available to farmers.
- There is a need to stop poorly informed and reductive farming advice.
- Agricultural advisory services must be independent.

Power

- Technology should be developed for a wide market and not just high profit, large-scale farms.
- Technology must not consolidate corporate control and increase supply chain centralisation.
- Technology must empower farmers and citizen users of technology.
- Innovation should be in the interests of all.
- Technology developers must accept liability when issues occur. Risk should not be pushed onto farmers.
- Technology should not consolidate profitability and restrict viability of farms

Participation/Accessibility

- Technology should be developed for a wide range of contexts.
- Users should be involved in the development of technologies.
- Local communities should be involved in decision making around technology.
- Technology should be widely accessible and affordable.

Jobs and Skills

- Technology should create and retain jobs and enhance job quality.
- Technology should not lead to a deskilling of the agricultural sector. It should not displace knowledge and experience but enhance skills.
- Impacts on employment should be measured and communicated.

Accountability and Transparency

- Data on impact of technologies and innovations needs to be transparent and widely accessible. This will enhance understanding of adverse impacts and incentivise resolutions.
- There is a need for greater clarity around the responsibility for impacts created using technologies. It must not allow actors to avoid taking responsibility for negative environmental and social impacts. Rules around liability need to be clear.

Agroecological System Alignment

- Technology must support a land sharing approach that integrates climate and nature friendly, healthy food production.
- Public funding of research should have to prove that it is beneficial to agroecology. This is related to the public goods provided by agroecology.
- Technology impact must be evaluated across multiple indicators and not limited to conventional metrics such as gross margin. Consideration of these integrated measurements must aim to reduce hidden costs and impacts.
- Technology must be developed for and compatible with increased diversity, and greater soil cover and soil health.
- Technology should be evaluated based on its alignment with the (10) agroecology principles.
- Technology must not have negative repercussions on animal welfare.

Appendix 2:
AgroEcoTech Indicator Long List

Area of Governance	Variable	Possible Indicators
Participatory Knowledge Generation	Farmer-to-farmer knowledge generation	Number of multi farmer grant applications Number of multi farmer research projects Number of national events encouraging farmer knowledge sharing Number of data technologies available that encourage farmers to share data The scale of investment in farmer data-sharing technologies/ innovations
	Farmer and researcher collaboration	Number of research projects involving farmers in a collaborative manner Number of research projects taking place on farms Number of grants structured to enhance farmer and researcher collaboration Number of research institutes with a major focus on farmer collaboration and on-farm research
	Data accessibility	Number of recorded farmer complaints to government departments about access to data Number of farmers involved in legal proceedings regarding access to data Farmer opinion about access to data The ratio of public to private big data sets collected on farms Number of public data sets considered accessible and usable for a UK farmer Average farmer spending on access to data Average quantity and diversity of data accessed by farmers
	Access to impartial advice	Appointed body for providing impartial advice on agroecological practice Number of farmers seeking advice from the appointed body annually Number of resources developed to inform farmers about good agroecological practice Number of farmers receiving resources on good agroecological practice annually Most stated source of advice for farmers

	Agroecological innovation in education	The number of UK universities/agricultural colleges with programmes teaching about agroecology and explicitly targeting agroecological food system innovation.
	Collaboration between disruptive technology start-ups and researchers	Number of collaborations between disruptive technology companies and researchers Number of grants in place to incentivise collaboration The scale of public investment in these collaborations Opinion of disruptive technology companies on the value and security of the collaborations and grants
Accessibility and Equity	Affordability	Number of technology rental and technology sharing schemes. Average farm expenditure on various categories of technologies The average cost of technologies needed to undertake certain tasks The average scale at which farms can access certain types of technologies
	Repairability	Presence of standards and regulation to enhance repairability Number of farmers reporting or seeking advice on the repair of different technologies.
	Interoperability	Presence of standards and regulation to enhance interoperability Number of farmers reporting complaints about lack of interoperability with certain types of technology
	Modularity	Presence of standards and regulation to enhance modularity Number of farmers reporting complaints about lack of modularity with certain types of technology
	Adaptability	Number of farmers reporting complaints about lack of compatibility of certain types of technology with their system

Accountability and Transparency	The review of technologies for investment	Presence of an interdisciplinary board appointed to review public/private investment in agricultural technology based on alignment with agroecological principles Presence of a framework for reviewing the alignment of investments with agroecological principles Number of investments considered good based on the application of the framework
	Integrated cost-benefit	Presence of a standardised integrated cost-benefit analysis to be used by public and private investors in agricultural technology Presence of procedure to propose opportunities for public financing that have high social and environmental benefits, but have low market value
	Lifecycle analysis	Presence of standardised lifecycle analysis methodology Presence of interdisciplinary body for developing and reviewing lifecycle analysis methodologies Regulation mandating the use of lifecycle analysis across all large industries
	Public awareness	Review of public sector investment available to the public Presence of regulations mandating that results of lifecycle analysis be made publicly available
	Public influence	Presence of a clear procedure for allowing the public to contribute to the review of public investment in agricultural technologies Number of projects to which the public contributed Public awareness of procedure for contribution Number of government-led co-design workshop between actors in the food sector and the public

To find out more visit:
www.soilassociation.org

Soil Association
Spear House, 51 Victoria Street, Bristol BS1 6AD
T 0117 314 5000
Registered charity no. 206862

Do you need this in an alternative format?
If you require this document in an alternative format, please call **0117 314 5001** or email **digitalteam@soilassociation.org** to request a copy.